Influence of Horizontal Curves on Speeds of Different Vehicle Categories

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Abstract. This study investigates the impact of road geometric features, specifically horizontal curves, on the speed parameters of various vehicle types in heterogeneous traffic conditions. Data were collected from two designated sections using video graphic techniques, enabling a comprehensive analysis of vehicle behavior. The findings indicate a significant decline in average speeds across all vehicle types on curved sections compared to straight sections, with an overall average speed reduction of approximately 11.619%. Additionally, the 85th percentile speeds decreased by an average of 13.043%, while the 50th percentile speeds showed a reduction of 10.714%. Notably, ANOVA analysis revealed significant differences in speeds among vehicle types, with the exception of autos and jeeps, which did not exhibit significant variance. These results highlight the critical influence of road geometry on vehicle dynamics, emphasizing the need for effective roadway design and traffic management strategies to enhance safety and efficiency in mixed traffic environments.

Keywords: Horizontal curves, Speed, ANOVA, Vehicle Categories, Heterogeneous Traffic Condition.

1 Introduction

Understanding vehicular speed dynamics is an essential component of modern traffic engineering, impacting safety, assessments, geometric road design, and congestion management. Speed, commonly measured in kilometers per hour, serves as a benchmark for traffic flow efficiency and the quality of service experienced by road users [1]. Evaluating how road design influences vehicle speeds enables engineers to develop safer, more consistent roadway environments and implement effective traffic control measures. Speed plays a pivotal role in evaluating roadway capacity and level of service. It serves as a critical parameter for accident analysis, where variations in speed can correlate with the frequency and severity of crashes. Moreover, speed management

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is fundamental in establishing traffic calming measures and signal coordination schemes. Effective speed regulation reduces speed disparities among vehicles, thereby minimizing accident risks associated with rapid deceleration or abrupt stops. A key application of speed studies is in setting appropriate speed limits. Speed limits help regulate vehicular movement, especially in environments prone to speed variability, such as near horizontal curves or steep gradients. By ensuring a uniform flow of traffic, speed limits mitigate severe accidents that often result from over-speeding or sudden braking. Thus, roadway designers must thoroughly understand how various geometric factors influence vehicle speeds [2].

Vehicle speed on roadways is influenced by a multitude of factors, including traffic mix, road surface condition, and the complexity of road geometrics. Roadway elements such as horizontal curves, lane width, and the presence of medians all affect how drivers perceive and adjust their speed [3]. For example, road surface irregularities or poorly designed curves can force drivers to decelerate, causing fluctuations in traffic flow and increasing the risk of collisions. Furthermore, mixed traffic conditions—where different vehicle types share the road—compound these variations, as larger vehicles like trucks respond differently to road features compared to passenger cars. Studies have demonstrated that geometric road features like horizontal curves significantly impact operating speeds. Curves with smaller radii tend to reduce vehicle speeds more than wider curves. Additionally, the presence of gradients and varying lane widths can either exacerbate or mitigate these speed reductions, depending on the driving environment. The interplay between these factors necessitates a holistic approach in traffic modeling and road design [4].

Researchers developed predictive models for operating speeds on rural four-lane highways, emphasizing the adverse impact of horizontal curves [5, 6]. Their research indicated a marked speed reduction when vehicles approached curves, with sharper curves causing more significant deceleration. Such findings underscore the necessity for gradual transitions in curve design to ensure driver safety and comfort. Similarly, researchers analyzed two-lane rural highways, focusing on how curve radius and the length of the approach tangent influence operating speed [7]. Their research revealed that longer approach tangents allow drivers to maintain higher speeds before decelerating, highlighting the need for strategic curve placement in highway design. Researchers explored how different vehicle types, specifically passenger cars and trucks, respond to road curves and grades [8]. Their findings showed that passenger cars are more sensitive to curve radii, while truck speeds are significantly influenced by steep grades. Such disparities necessitate the inclusion of vehicle type considerations in speed prediction models, as a one-size-fits-all approach may overlook critical safety concerns for heavier vehicles. Researchers utilized drones to capture real-time speed data at freeway work zones, demonstrating the technology's effectiveness in identifying high-risk areas [9]. Their analysis showed that merging zones are critical segments where speed management is most needed, especially for differentiating between trucks and passenger vehicles. The use of drones has set a new standard for precision in traffic studies, providing invaluable insights into the behavior of vehicles in diverse traffic conditions. Researchers suggest that driver behavior, such as lane-changing tendencies, must be considered when designing horizontal curves [10]. Incorporating wider shoulders and gradual curve transitions can mitigate the adverse effects of sharp curves, thereby enhancing overall road safety. As urbanization continues and road networks become more complex, understanding vehicular speed characteristics remains a top priority. The rise of autonomous vehicles (AVs) introduces new challenges and opportunities in speed management. Future research must explore how AVs interact with traditional road geometries and whether existing speed prediction models remain valid. Additionally, the integration of vehicle-to-infrastructure (V2I) communication can provide real-time speed adjustment recommendations, further reducing accident risks [11].

This study aims to further investigate the effects of horizontal curves on the speeds of various vehicle types in mixed traffic conditions. By examining these interactions, the research seeks to provide insights into how road design influences traffic flow and vehicle performance, contributing to the development of more efficient and safer road networks.

2 Locations for Data Collection

Two sections were chosen for data collection to study the effect of road geometrics on speed of the traffic flow and details are given in Table 1. A straight section of 50 m at Ongole was chosen for the collection of speed and flow data. A curved section of 50 m at Ongole was chosen for the comparative study. The radius of the curve at which data was collected is 300 m. The study utilized a video graphic technique for data collection, providing an effective and accurate means of capturing detailed traffic information. Both the study locations chosen are two lane roads and the length of the section considered is 50 m at both the locations.

Table 1. Details of Study locations for data collection

Location No	Location name	Straight/ Curved	Length of section(m)	Width of section(m)
1	Ongole	Curved	50	7.5
2	Ongole	Straight	50	7.5

Both the study locations are two lane roads.

3 Speed and Volume Data

The speed data and classified volume data for both curved and straight sections were retrieved from the traffic videos. Due to the heterogeneous nature of traffic, the speeds obtained for each type of vehicle was used for the analysis. Various speed percentiles such as 98th, 85th, 50th and average speed values were used to compare the effect of the curve on the speed characteristics. The standard deviation and coefficient of variation were used to represent the variations in the data. ANOVA tests were done to find out whether there is any significant difference in the speed values for each vehicle type and also for all the vehicles considered together. The standard deviations and coefficient of variation for the speeds of vehicles in the two locations are as given in Table 2. The data provides a detailed analysis of vehicle speeds across different types and road geometries, specifically straight and curved sections. Vehicles generally exhibited higher mean speeds on straight sections compared to curved ones, highlighting the significant impact of road design on performance. For example, cars recorded a mean speed of 64.55 km/h on straight roads, which is approximately 19.7% faster than their speed on curved roads, where they averaged 53.97 km/h. In contrast, auto rickshaws had the lowest mean speed on straight sections at 41.91 km/h, a decline of about 2.8% from their curved section speed of 40.49 km/h. The standard deviations across the vehicle categories indicate a relatively consistent performance, with coefficients of variation (CV) ranging from 0.13 to 0.31, reflecting varying degrees of speed dispersion. Notably, the CV values for curved sections are generally higher, suggesting increased variability in speeds due to the challenges posed by curvature. This analysis emphasizes the influence of road characteristics on traffic flow dynamics and vehicle behavior, demonstrating how different geometries can affect overall speed performance in mixed traffic conditions.

Table 2. Standard Deviations and Coefficients of Variation

Vehicle Type	Type of Section	Sample Size	Mean Speed	Standard Deviation	Coefficient of Variation
Two Wheeler	Straight	412	50.24	9.77	0.19
	Curved	1485	46.09	9.42	0.20
Auto	Straight	74	41.91	5.63	0.13
	Curved	229	40.49	7.33	0.18
Car	Straight	435	64.55	12.51	0.19
	Curved	1273	53.97	10.38	0.19
Jeep	Straight	32	55.57	10.40	0.18
	Curved	64	53.34	11.34	0.21
Mini bus	Straight	23	55.44	8.87	0.16
	Curved	26	46.91	12.84	0.27
Bus	Straight	100	56.85	9.43	0.16
	Curved	199	42.52	13.23	0.31
Mini Truck	Straight	283	53.37	8.69	0.16
	Curved	424	48.12	8.07	0.16
Truck	Straight	219	47.45	7.68	0.16
	Curved	477	45.14	8.44	0.18
All Vehicles	Straight	1571	54.57	12.15	0.22
	Curved	4176	48.23	10.55	0.21

IV Comparison of Percentage Reduction in Speed

To assess the effect of the curve on vehicle speeds, the study compared the percentage differences in percentile speed values for various vehicle types. Table 3 summarizes these speed comparisons for each vehicle category. The findings reveal that all vehicle types experienced a reduction in the 85th, 50th, and mean speed values on the curved sections compared to those measured on the straight sections. The 98^{th} percentile values for auto, jeep, minibus and truck shows that there is an increase in the speed in the curved section. This variation in the trend could be due to some other influencing factor which is not revealed through this study. The percentage reduction in speeds for bus is the maximum and that for auto is the minimum. The speed characteristics of various vehicle types were analyzed across straight and curved road sections, revealing notable variations in speeds. At the 98th percentile, two-wheelers experienced a speed reduction of approximately 7.3%, decreasing from 71.052 km/h on straight roads to 65.853 km/h on curved roads. In contrast, auto rickshaws exhibited an increase in speed, showing a variation of -14.67%. Cars had a significant drop of 14.8%, from 88.025 km/h to 75 km/h, while jeeps showed a minor reduction of about 1.9%. Mini buses maintained a slight speed variation of 0.37%, whereas buses experienced a reduction of 7.7%. Overall, the average percentage reduction at the 98th percentile for all vehicles was around 13.16%. At the 85th percentile, two-wheelers showed an 8.16% reduction, and cars experienced a more pronounced decrease of 16.67%, leading to an average reduction of 13.04%. The 50th percentile data revealed that two-wheelers decreased by 7.63%, with cars showing a 16% drop and buses experiencing a significant reduction of 33.80%. The average reduction in mean speed across all vehicles was approximately 11.62%, indicating that larger vehicles tend to experience greater reductions in speed than smaller vehicles. This analysis emphasizes the impact of road geometry on vehicle speed and the potential for traffic flow inefficiencies, underscoring the importance of careful road design considerations.

Table 3. Comparison of the Speed Values for Each Type of Vehicle

Speed Characteristic	**Type of Vehicle**	**Two Wheeler**	**Auto**	**Car**	**Jeep**	**Mini Bus**	**Bus**	**Mini-Truck**	**Truck**	**All Vehicles**
98^{th} Percentile Speed	Straight	71.05	53.51	88.02	73.105	69.489	75.042	61.363	62.27	81.81
	Curved	65.85	61.36	75	74.472	69.230	69.230	65.132	62.79	71.05
85^{th} Percentile Speed	Straight	60	47.41	77.14	68.192	63.837	65.853	61.363	55.10	67.50
	Curved	55.10	47.36	64.28	65.853	58.258	57.446	56.250	53.78	58.69
50^{th} Percentile Speed	Straight	49.54	41.53	64.28	56.25	56.25	57.446	52.941	47.36	54
	Curved	45.76	40.29	54	52.432	47.426	38.028	48.214	45	48.21
Mean Speed	Straight	50.244	41.913	64.556	55.575	55.447	56.854	53.370	47.456	54.571
	Curved	46.095	40.491	53.973	53.341	46.918	42.524	48.120	45.143	48.230
Percentage	98^{th} Percentile	7.317	-14.67	14.797	-1.870	0.372	7.745	-6.141	-0.824	13.157

Reduction in Speed	85^{th} Percentile	8.163	0.089	16.666	3.429	8.738	12.765	8.333	2.388	13.043
	50^{th} Percentile	7.634	2.985	16	6.787	15.685	33.802	8.928	5	10.714
	Mean	8.257	3.391	16.394	4.019	15.382	25.203	9.837	4.873	11.619

5 ANOVA Test Results

The ANOVA test was done to compare the speed values of curved and straight sections. This test was done to find out whether there is any significant difference between the speeds of each type of vehicle in the two sections. Table 4 gives the results of the test. The analysis of the results shows that there is no significant difference in the speeds of auto and jeep. For all other types of vehicles, the difference is significant. The analysis of vehicle speeds across different types of sections revealed significant differences in average speeds for various vehicle types. For two-wheelers, the average speed was **50.24 km/h** on straight sections with a variance of **95.52**, while on curved sections, it was lower at **46.09 km/h**. The F-test indicated that the difference was significant, with an F value of 61.54, exceeding the critical value of 3.84. In the case of autos, the average speed was 41.91 km/h on straight sections and 40.49 km/h on curved sections, but the F value of 2.33 indicated that this difference was not significant (F critical was 3.87). For cars, significant differences were also observed, with an average speed of 64.55 km/h on straight sections and 53.97 km/h on curved sections, producing an F value of 301.69, well above the critical value of 3.84. Jeeps showed an average speed of 55.57 km/h on straight sections and 53.34 km/h on curved sections, but the F value of 0.72 indicated no significant difference (F critical was 3.95). Mini buses had a significant difference in speeds, with 55.44 km/h on straight sections and 46.91 km/h on curved sections, resulting in an F value of 7.12, which surpassed the critical value of 4.04. Buses exhibited significant differences in speed, averaging 56.85 km/h on straight sections compared to 42.52 km/h on curved sections, with an F value of 93.28 exceeding 3.87. Mini trucks showed a significant difference as well, averaging 53.37 km/h on straight roads versus 48.12 km/h on curved roads, with an F value of 67.44 (critical value 3.85). Trucks also displayed significant speed differences, averaging 47.45 km/h on straight sections and 45.14 km/h on curved sections, with an F value of 11.89. Finally, for all vehicles combined, the average speed on straight sections was 54.57 km/h, while it dropped to 48.23 km/h on curved sections, producing an F value of 378.41, which was significantly higher than the critical value of 3.84.

Table 4. Summary of ANOVA Results

Type of Vehicle	**Type of Section**	**Average Speed**	**Variance**	**Sample Size**	**Degree of Freedom**	**F Value**	**F Critical**	**Significant/Not Significant**
Two Wheeler	Straight	50.24	95.52	412	1896	61.54	3.84	Significant
	Curved	46.09	88.74	1485				
Auto	Straight	41.91	31.77	74	302	2.33	3.87	

	Curved	40.49	53.84	229				Not Signifi-cant
Car	Straight	64.55	156.69	435	1706	301.69	3.84	Significant
	Curved	53.97	107.93	1273				
Jeep	Straight	55.57	108.17	32	97	0.72	3.95	Not Signifi-cant
	Curved	53.34	128.68	64				
Mini Bus	Straight	55.44	78.77	23	48	7.12	4.04	Significant
	Curved	46.91	164.89	26				
Bus	Straight	56.85	89.09	100	298	93.28	3.87	Significant
	Curved	42.52	175.18	199				
Mini Truck	Straight	53.37	75.62	283	706	67.44	3.85	Significant
	Curved	48.12	65.17	424				
Truck	Straight	47.45	59.10	219	695	11.89	3.85	Significant
	Curved	45.14	71.38	477				
All Vehicles	Straight	54.57	147.73	1571	5746	378.41	3.84	Significant
	Curved	48.23	111.33	4176				

6 Conclusions

This study highlights the critical role of road geometry in influencing traffic stream speeds across various vehicle types. The findings reveal significant differences in vehicle speeds between straight and curved sections, demonstrating that vehicles generally exhibit lower speeds on curves. Specifically, the analysis showed that the average speed of vehicles decreased on curved sections, with the following percentage reductions noted: the 85th percentile speeds decreased by an average of 13.043%, the 50th percentile speeds declined by approximately 10.714%, and the mean speeds dropped by around 11.619% across all vehicle types. Among these, buses experienced the most substantial percentage reduction in speed, while trucks exhibited the least reduction, indicating variability in how different vehicle types respond to changes in road curvature. Interestingly, the analysis of the 98th percentile speeds highlighted a contrasting trend, as certain vehicle types, including autos, jeeps, minibuses, and trucks, demonstrated an increase in speed on curved sections, suggesting that additional influencing factors not explored in this study may be at play. The 98th percentile speed for minibuses on curved sections, for instance, was recorded at 74.472 km/h, showing a potential behavioral shift in driver response to road geometry. Statistical analysis conducted through ANOVA confirmed significant differences in speeds across most vehicle types when comparing straight and curved sections, with the exception of autos and jeeps, which did not show significant variance. This lack of significant difference for autos and jeeps suggests that these vehicles might be less affected by curvature, possibly due to their smaller size and maneuverability, or it may indicate a need for further exploration into the unique characteristics of these vehicle types.

Overall, the results of this study underscore the importance of considering road geometry in traffic planning and design. Understanding how different vehicles respond to road curvature can inform roadway design practices aimed at improving safety and efficiency on our road networks. Future research should explore the underlying factors contributing to the observed variations in vehicle speeds, particularly for those vehicle types that exhibited unexpected speed behaviors on curved sections. Additionally, integrating a broader range of influencing variables, such as weather conditions, driver behavior, and traffic density, could provide a more comprehensive understanding of traffic dynamics in heterogeneous conditions.

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