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Impact of the Direction of the Horizontal Curves on the Operating Speed Performance of the Vehicles on Hilly Terrain

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Abstract

The operating speed models are necessary to evaluate the geometric design consistency as well as the road safety. The speeds of vehicles moving on the hilly terrain are influenced by several factors including the geometric details of the highway. Present study investigates the impact of the direction of the horizontal curves on the operating speed. This study has also analysed the impact of gradients on the operating speeds adopted on the horizontal curves. The Pearson correlation analysis shows that the geometric parameters of the horizontal curve have more impact on the operating speed of vehicles moving on the left turning curves (inner lane) than that are moving on the right turning curves (outer lane). Moreover, the speed reduction from the approach tangent section to the middle of the horizontal curves was more for the left turning than the right turning curves. Finally, the operating speeds on the left turning and right turning curves were compared for different ranges of vertical gradients. It was found that the operating speed on the right turning curves was higher than the left turning for steep upgrades, whereas, that the operating speed on the left turning curves was higher than the right turning for steep downgrades. This paper concludes that, in case of the hilly terrain, the operating speeds of vehicles are significantly influenced by the direction of the curve traversed by the driver.

Keywords: Operating Speed; Horizontal Curve; Direction of Curve; Operating Speed Modelling

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1. Introduction

Achieving consistent geometric design is an important goal in the highway design to ensure safe, economical, and smooth operation of the vehicles. Modeling operating speed is an inevitable process in the geometric design consistency analysis as well as in the studies related to road safety. The operating speed can be influenced by many factors such as the environment, topography, vehicle type, and the driver characteristics. However, the geometric design parameters are crucial for modeling the operating speed. Many studies have reported that majority of the accidents occur on the horizontal curves. Thus, the operating speed of vehicles while negotiating the horizontal curve needs to be thoroughly investigated.

Nomenclature

HCM	Heavy construction machinery
EME	Earth moving equipment
MAV	Multi axle vehicle (4-6axles)
LCV	Light commercial vehicle
LGV	Light good vehicle
L_t	Transition Length
L_c	Length of the Curve
e	Super elevation
Δ	Deflection angle
R	Curve radius
L_{at}	Length of approach tangent
L_{et}	Length of exit tangent
DC	Degree of Curvature
G	Grade
V_{85}^{C}	Operating speed of car
V_{85}^{T}	Operating speed of empty truck
V_{85}^{LT}	Operating speed of loaded truck

Researchers have identified numerous geometric design parameters that influence the operating speed performance of the vehicles. Considering the geometric parameters, numerous operating speed models were developed (e.g., Hassan et al., 2000; Javier and Torregrosa, 2013; Krammes et al., 1995; Lamm et al., 1988). Limited studies have been found corresponding to the operating speed modeling at the horizontal curves combined with the vertical curves (e.g., Abbas and Adnan, 2010; Gibreel et al., 2001; Jacob et al., 2013). Selection of the geometric parameter is the toughest task for such curves and requires extensive surveys and statistical analyses.

The past studies identified three inter-related problems that lead to driver errors on the horizontal curves. Driver attention, misperception of the speed and curvature, and poor lane positioning are the three factors that lead to the driver errors (Caliendo et al. 2007). Such driver errors lead to severe crashes and may cause loss of life and/or a considerable economic loss. Since the driving is associated to several psychological processes, driving on the curves has become research interest for many psychologists. Statistical analyses shows that about 80% of the driving information is attained from the visual observation (Kowler 2011) and the perceptions. Researchers found that the drivers go through added mental workload when negotiating the curves (Li et al. 2014).

Literature reports that the right turn curves having higher radii are more dangerous compared to the left turn curves. Sharp curves are dangerous in case of both the left and right turning curves (Othman et al., 2009). Misaghi & Hassan (2005) developed an operating speed differential model that incorporates the turning direction of the curves and it suggests that the left turning lanes require a higher speed reduction compared to the right turning. This was also confirmed by Liu et al., (2017) and they found that the drivers are more careful and concentrate more on the left turning curves than the right turning as they have a subjective feeling that it is more dangerous. All these studies were conducted in countries where the drivers drive on the right side of the road.

Literature suggests that the drivers' perception also influences the operating speed. A few researchers have mentioned the importance of the direction of curve on the operating speed performance of the vehicles. The influence of the direction of the curve on the operating speed can be easily related to the driver perception.

Present study investigates the impact of the direction of the horizontal curves on the operating speed. The main goal of the study is to check whether there exists any significant difference in the operating speed of vehicles when moving on the left and right turning curves. The difference in operating speed could be due to various psychological factors of the drivers, perception towards the geometry, or may be due to other reasons. This has been analyzed in terms of the reduction in the operating speed while moving from the approach tangent to the mid-point of the curve. This study has also analyzed the impact of gradients on the operating speeds adopted on the horizontal curves. The scope of the study is limited to the daylight condition, dry pavement, and the drivers drive on the left hand side of the highway. The road section was selected based on the following criteria:

i. A rural road with low flow levels, where the vehicles are moving at free flow speed, was selected.

ii. Road sections have less or no interference from the public, away from intersections, public places etc.

A total number of 361 accidents were recorded on the selected road stretch between May 2013 and April 2018.

2. Data Collection

The geometric data and the free flow speed data were collected from the Shillong bypass road connecting NH-40 and NH-44, in Meghalaya, India. The study stretch is a 48.765 km long two-lane undivided rural highway with both directions of travel, comprising 253 horizontal and 175 vertical curves. The speed data were collected from 29 horizontal curves with a constant vertical grade, for both the directions of travel. Table 1 shows the statistical summary of the 58 curves considered for the analysis in the present study.

Table 1. Statistics of the Parameters Considered for the Analysis

Parameter	Min	Max	Mean	Standard Deviation
Transition Length (m)	15	55	36.03	11.80
Length of Curve (m)	23.21	162.14	55.81	31.16
Super elevation (%)	0.03	0.10	0.07	0.03
Deflection angle (deg)	4.89	169.55	47.43	34.40
Curve radius (m)	60	500	167.93	120.45
Length of entering tangent (m)	2	186.56	58.17	47.86
Length of exit tangent (m)	2	186.56	58.17	47.86
Degree of Curvature (deg)	3.49	29.11	14.47	6.64
Grade (%)	-6	6	0.00	4.99
Road width at circular curve (m)	6.7	9.6	7.7	0.85

Fig. 1 shows the 30-day average traffic composition observed on this road stretch. This figure clearly shows that the heavy vehicles are the major components of the traffic stream.

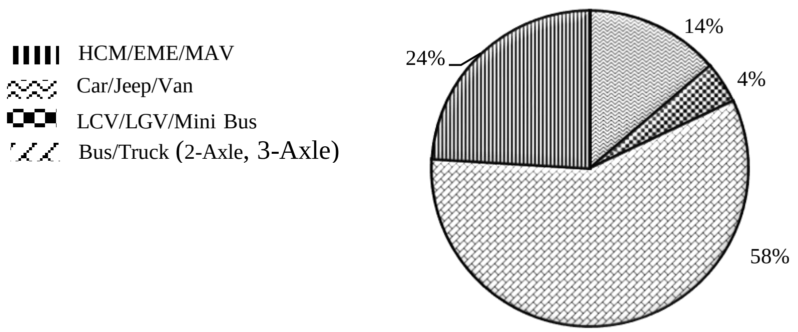

Fig 1. Average composition of the traffic stream

The speed data were collected at the middle of the horizontal curve and on the tangents (at 60m from the beginning of the transition curve) using Radar Gun, during clear weather and dry pavement conditions. The free flow speeds of 100 vehicles from each category of the vehicle, at the middle of the curve and tangent, were collected. While collecting the data it was ensured that all the vehicles were moving freely without any external influences.

Before performing the analysis, the outliers in the observed speed data were removed by performing the quartile analysis. The outliers in the speed data are defined as those speed values that fall outside $Speed^+$ or $Speed^-$, where the $Speed^+$ and $Speed^-$ are defined as follows.

$$Speed^+ = \max_{v_i} \{v_i | v_i < (Q_3+1.5*IQR)\} \quad (1)$$

$$Speed^- = \min_{v_i} \{v_i | v_i > (Q_1-1.5*IQR)\} \quad (2)$$

Where Q_1, Q_3 and IQR are the 25th percentile speed, 75th percentile speed, and the interquartile range ($IQR=Q_3-Q_1$) at each level, respectively. Figure 2 shows the observed speed data along with the outlying speed values.

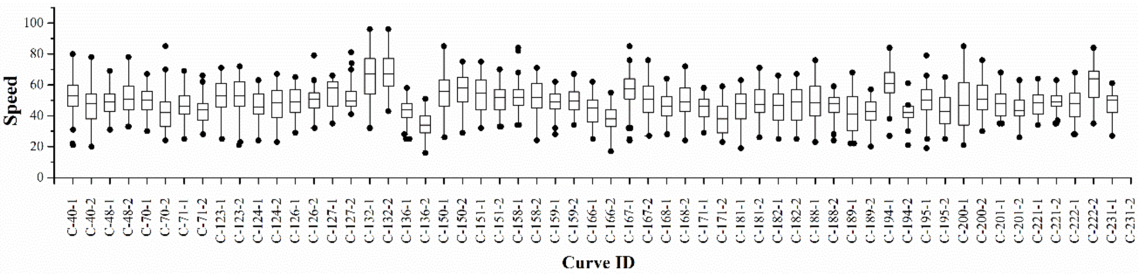

Fig 2. The observed speed data at different curves along with outliers

In this study three categories of vehicle groups (Car, Truck, and Loaded Truck) were considered for the analysis. Analysis of Variance (ANOVA) test has been performed on all the horizontal curves selected to check whether a statistically significant difference exists between the speeds of the vehicle classes. Table 2 shows the operating speed of the three types of vehicles on three different horizontal curves at the middle of the curve along with the ANOVA test results. As $F>F_{critical}$ for p value less than 0.05, the free flow speed of the various categories of vehicles are significantly different from each other.

Table 2. Results of ANOVA test

Curve No.	V_{85}^{C}	V_{85}^{T}	V_{85}^{LT}	F	P-value	$F_{critical}$
40	57.2	46	30	143.41	3.66E-41	3.03
123	63.3	54	43	60.64	6.24E-20	3.05
126	58	48.7	32.75	140.24	3.74E-35	3.05

3. Analysis of the drivers' speed choice

The reduction in the operating speed of vehicles while negotiating the horizontal curves with constant grade was analysed. The impact of the direction of the change in curvature was investigated, as it may influence the drivers' speed choice due to various psychological reasons. To perform this analysis, a flat horizontal curve with similar characteristics in both the directions was identified. This curve is free from the other external influences, and the operating speed for both the directions was compared. Fig. 3 shows the variation of the operating speed at various points of the curve for both the left and the right directions, for each vehicle category. The figure depicts the significance of the turning direction of the curve on the operating speed for all the classes of vehicles.

1 = Approach Tangent; 2 = Curve Entry; 3 = Mid of Curve; 4 = Curve Exit; 5 = Exit Tangent;

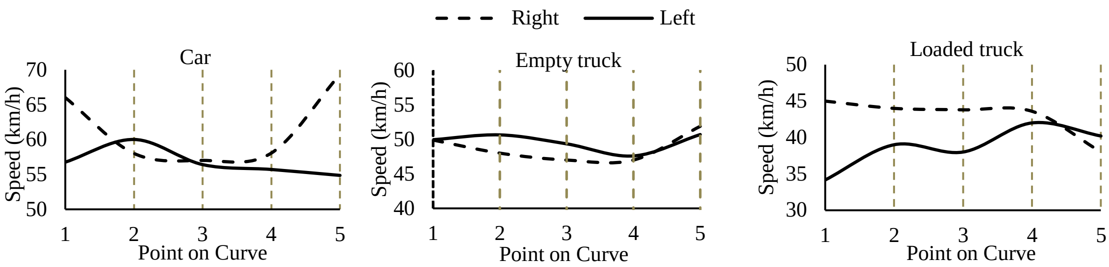

Fig 3. Operating speed of different classes of vehicles at different points on curve

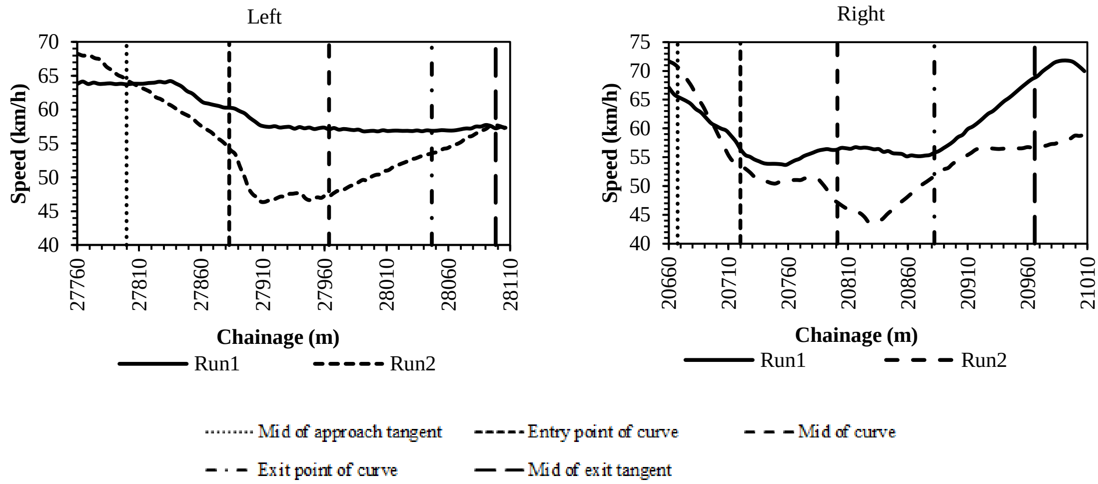

Fig 4. Speed profile of the instrumented passenger car

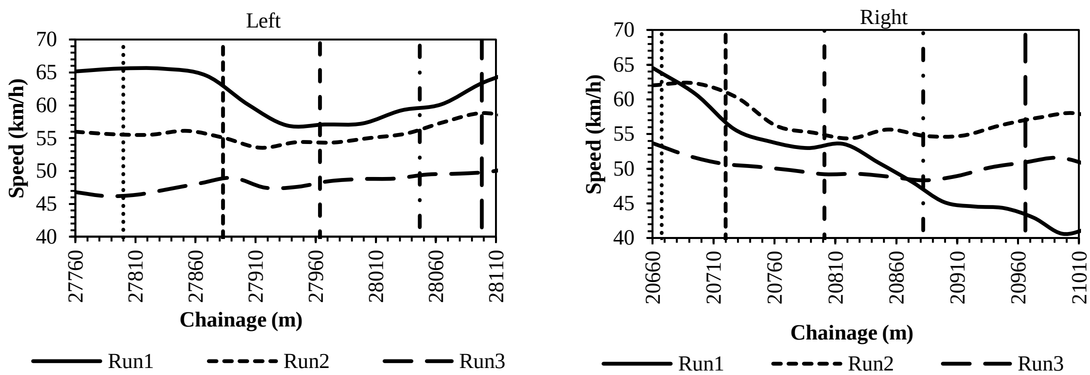

Fig 5. Speed profile of the instrumented truck

To verify the above findings, the speed of an instrumented passenger car and truck haves also been analysed. The vehicles were equipped with the V-Box to obtain the speed profile when traversing the horizontal curve. The speed was collected for a couple of runs (2 runs for car, 3 runs for truck) at free flow conditions during day time on dry pavement. The speed profile for the passenger cars and the trucks were extracted from the V-Box and shown in Figures 4 and 5, respectively. The figure shows that for both the vehicles the reduction in the free flow speed of the right turning drivers is more compared to the left turning drivers. The authors have put forward that the turning direction of the drivers could be one of the deciding factors of the operating speed preferences. It was assumed that the speed preferences of the drivers would be different on the left and right turning horizontal curves. The correlation analysis of the operating speed and different geometric parameters was performed separately and discussed in the following sections.

3.1 Correlation Analysis

The Pearson's correlation analysis was performed to index the degree of linear relationship between the variables (cf., Cohen et al., 2003). The Pearson's coefficient (r) has been estimated as follows,

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \tag{3}$$

Table 3. Pearson's Correlation coefficients between the left turning drivers' speed and various important geometric parameters

	L_t	L_c	e	R	Δ	DC	G	L_{at}	L_{et}	V_{85}^C	V_{85}^T	V_{85}^{LT}
L_t	1											
L_c	0.28	1										
e	0.95	0.30	1									
R	-0.87	-0.23	-0.85	1								
Δ	0.74	0.74	0.73	-0.66	1							
DC	0.85	0.25	0.83	-0.87	0.80	1						
G	0.35	0.15	0.30	-0.23	0.37	0.44	1					
L_{at}	-0.19	0.08	-0.16	0.34	-0.04	-0.22	-0.06	1				
L_{et}	-0.02	0.17	-0.06	0.13	-0.05	-0.19	-0.20	-0.17	1			
V_{85}^C	-0.63	-0.21	-0.57	0.74	-0.56	-0.75	-0.32	0.37	0.11	1		
V_{85}^T	-0.48	-0.10	-0.44	0.51	-0.40	-0.59	-0.52	0.06	0.16	0.71	1	
V_{85}^{LT}	-0.47	-0.27	-0.51	0.48	-0.44	-0.53	-0.48	-0.04	-0.03	0.49	0.61	1

Table 4. Pearson's Correlation coefficients between the right turning drivers' speed and various important geometric parameters

	L_t	L_c	e	R	Δ	DC	G	L_{at}	L_{et}	V_{85}^C	V_{85}^T	V_{85}^{LT}
L_t	1											
L_c	0.28	1										
e	0.95	0.30	1									
R	-0.87	-0.23	-0.85	1								
Δ	0.74	0.74	0.73	-0.66	1							
DC	0.85	0.25	0.83	-0.87	0.80	1						
G	-0.35	-0.15	-0.30	0.23	-0.37	-0.44	1					
L_{at}	-0.02	0.17	-0.06	0.13	-0.05	-0.19	0.20	1				
L_{et}	-0.19	0.08	-0.16	0.34	-0.04	-0.22	0.06	-0.17	1			
V_{85}^C	-0.21	-0.11	-0.26	0.33	-0.25	-0.32	-0.19	0.02	0.17	1		
V_{85}^T	0.01	-0.07	-0.05	0.15	-0.07	-0.10	-0.38	-0.03	-0.02	0.78	1	
V_{85}^{LT}	0.17	0.06	0.10	-0.05	0.14	0.12	-0.56	-0.10	-0.09	0.65	0.83	1

Tables 3 and 4 show the correlation coefficients corresponding to the drivers' operating speed on the left and right turning curves, respectively. The parameters with correlation coefficients above 0.35 were considered as moderately correlated. It is evident from the table that many geometric characteristics influence the decision of the operating speed of the left turning drivers compared to the right turning. For the left turning curves, the geometric parameters such as the length of transition curve (L_t), super-elevation (e), radius (R), deflection angle (Δ), and the degree of curve (DC), are highly correlated to the operating speeds corresponding to all the vehicle types. Besides the above, the operating speed of the loaded and the empty trucks were also influenced by the grade (G). In case of the right turning curves, the only significant correlation was found between the operating speed of the empty and loaded truck and the grade (G).

3.2 Comparison of the Operating Speed on the Left and Right turning Horizontal Curves with vertical gradient

This section analyses the operating speed of the vehicles moving on the left turning and the right turning horizontal curves, with a similar range of grades. Firstly, the operating speed reduction from the approach tangent to the mid-point of the curve is analysed. Secondly, the operating speed at the centre of the horizontal curve is compared between the left and right turning curves for different grade categories.

The operating speed reduction from the tangent section to the middle of the horizontal curve was calculated for all the 58 curves. It was found that the average operating speed reduction for the left turning (3.82km/h for passenger car, 2.6km/h for empty truck and 1.02 km/h for the loaded trucks) was higher than that observed on the right turning (1.77km/h for passenger car, -0.78km/h for empty truck and 0.8 km/h for loaded trucks). This can be attributed to the direction of the curve and the driver’s perception about the combined geometry of the horizontal curve with the vertical gradients.

The left turning and the right turning curves were categorized based on the superimposed vertical gradients. The operating speeds were calculated at the mid-points of the horizontal curves. For all such sections considered in the present study, the vertical gradient ranges from +/-2% to +/-6%. The operating speeds of the passenger cars, empty and loaded trucks at the middle of the curve were averaged for various grade ranges and are shown in Table 5. The averaged operating speed observed on the left turning and the right turning horizontal curves were compared. It was found that the operating speed on the right turning curves was higher than the left turning curves for the downgrades ranging between 2 to 4% as well as for the upgrades ranging between 3 to 6%. Whereas, the average operating speed on the left turning curves was higher than the right turning for downgrades ranging from 4 to 6% and the upgrades from 2 to 3%. This highlights the significant difference between the operating speed on the left turning and the right turning horizontal curves.

The reason for this significant difference in operating speed on left and right turning horizontal curves could be due to the safety consideration of the drivers as well as their psychological aspects. These two aspects could be influencing the drivers’ perception of the road and their speed selection. The impact of the geometric parameters of the road alignment on the operating speed for the left and right turn curves are also different as discussed in the previous section. Other reason could be that even when the geometry for the left and right turning curves is similar, the consistency in the operating speed may differ.

Table 5. Operating speed Comparison between the Left and Right turn horizontal curves and the Tangent speed for different grade categories

Grade categories	Curve direction	Speed at Curve $AvgV_{85}^{C}$ (km/h)	$AvgV_{85}^{T}$ (km/h)	$AvgV_{85}^{LT}$ (km/h)	Remark
[-6 to -5)	Right	58.47	50.65	39.40	Rt<L
	Left	64.31	53.51	40.44	
[-5 to -4)	Right	60.01	50	44.98	Rt<L
	Left	61.91	51.36	44.39	
[-4 to -3)	Right	69.32	57.1	48.5	Rt>L
	Left	60	52.3	47	
[-3 to -2)	Right	61.55	48.67	43.67	Rt>L
	Left	56.25	45	38	
(2 to 3]	Right	52.8	43.25	28	Rt<L
	Left	60.1	48.17	34.4	
(3 to 4]	Right	64.35	53.45	46.57	Rt>L
	Left	58.97	50.15	38	

(4 to 5]	Right	55.31	45.8	28.58	Rt>L except loaded truck
	Left	53.8	43.8	36.66	
(5 to 6]	Right	59.12	46.2	30.78	Rt>L except loaded truck
	Left	58.1	44.76	30.81	

Note: Rt and L indicates operating speed on the right turning and the left turning curves respectively.

4. Conclusion

The present study has analyzed the operating speed performance of the passenger cars, loaded trucks, and the empty trucks moving on the roads passing through hilly terrain. Correlation matrix was used to identify the exploratory variables that satisfy 95% confidence level. The correlation analysis shows that the geometric parameters are significantly correlated to the operating speed on the left turning curves. The results show that the direction of the horizontal curve has significant impact on the operating speed. It has been observed that the reduction in the operating speed from the approach tangent to the middle of the horizontal curve is more in case of the left turning curves compared to the right turning. When the curves are superimposed with the steep upgrades, the average operating speed is higher for the right turning curves than the left turning. When the curves are superimposed with the steep downgrades, the average operating speed on the left turning curves was higher than the right turning curves. From the above observations, it can be concluded that the operating speed of vehicles moving on the hilly terrain are significantly influenced by the direction of the curves. The results indicate that a left turning and a right turning horizontal curve, with a similar geometry, may not exhibit similar consistency in terms of the operating speeds.

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