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Operating speed differential model for heavy vehicles using GPS driving data

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Abstract

It is well known that the operating speed varies continuously from the approach tangent to curve on the highways. In other words, it indicates the lack of consistency in geometric design element or combination of the design elements which fail to meet the driver's expectations to maintain the consistent operating speed. It is necessary to evaluate the inconsistency in highway geometric design elements by continuous measurement of the operating speed along the tangent to curve. The current study analyses and models the speed differential along the approach tangent-to-curve of the highway alignment. The data was collected for the heavy vehicles plying on the rural state highway and the major district road having geometrically constrained elements. High-end GPS data loggers were fixed in the vehicles to collect the required data. Variables such as speed, lateral-longitudinal acceleration/deceleration and temporal and spatial coordinates, of the vehicles were analysed, and models were developed to predict the 85th percentile speed differential ($\Delta_{85}V$) using continuous speed profile data. The analysis results revealed that, most of the times vehicle starts to decelerate near the approach tangent which continuous to the curve portion where it reaches minimum speed and again accelerates in the curve portion to the departure tangent till it attains the free-flow speed. The insights from the study can be used to evaluate the consistency in the geometric design elements of the rural highways for the heavy vehicles observed in developing world traffic.

Keywords: Operating speed; continuous speed profile; driver's expectations;design consistency;rural highway.

1. Introduction

The importance of the highway infrastructure lies in the safe and efficient transport of people and goods from one place to the other. The non-urban roads in India as per IRC 73-1980 are classified in to (i) National Highway (NH), (ii) State Highway (SH), (iii) Major District Road (MDR), (iv) Villager roads (VR), and (v) Other District roads (ODR). For these highways, geometric design elements should be designed to maintain the harmonious and homogenous operating speed along the highway. Among the various geometric design elements, horizontal curve forms the significant design element as it links the tangents to change the direction of the alignment. The study relates the road safety concerning tangent to curve design consistency.

Design Consistency is defined as the conformance of the geometric features of a road with drivers' expectations (Nicholson 1998). In other words, it indicates that geometric design features are not meeting driver's expectations to maintain consistent operating speed. The consistency in the operating peed is not achieved at the tangent-to-curve transition. It results in the speed reduction, i.e.; the vehicle starts to decelerate at the approach tangent continuing in the curve portion resulting in speed reduction along the tangent to the curve. This results in the sudden change in the speed at geometrically constrained curves leading to critical maneuverers increasing the risk of overturning and/or the risk of collision (Krammes 1997; Ottesen & Krammes 2000). Hence it is necessary to evaluate the inconsistency of geometrically constrained road elements such as curvatures, and one of the current methods is based on the measurement of the operating speed differential of the vehicles on the successive geometric elements, i.e., on the tangent to the curve (Misaghi & Hassan 2005).Initially, in the past literature, it was assumed that the speed remains constant along the horizontal curves and all the acceleration and deceleration were assumed to occur on the approach and departure tangent respectively (Lamm et al. 1988; Fitzpatrick & Collins 2000; and Ottesen & Krammes 2000). As per the above assumption, spot speed measurement was taken at the midpoint of the horizontal curve and rest of the spot speeds were measured at different locations on the approach and departure tangents which varied from one study to the other. Apart from the radar gun, equipment's like traffic counters/classifiers, video camera, and stopwatch were used to obtain the speed data. One of the drawbacks of the spot speed study was the difficulty involved in finding the beginning and the endpoints of acceleration and deceleration for the vehicles on the geometrically constrained road elements. Later with the advancement in the literature, dynamic GPS data logger and driving simulator were used to get the continuous speed data to develop 85th percentile operating speed differential model. The proposed study uses GPS data logger mounted on the heavy vehicle to trace the continuous operating speed and to develop reliable operating speed differential model along the tangent-to-curve to evaluate the design consistency for MDR and SH. The heavy vehicles were selected for the study as they represent the major traffic volume on the selected stretches.

2. Objectives

The prime objectives of the study are; (a) to measure the inconsistency in the operating speed along the tangent-to-curve and to develop operating speed differential model ($\Delta_{85}V$). (b) To compare and develop relationship between the 85^{th} percentile speed differential ($\Delta_{85}V$) and the differential of the 85^{th} percentile operating speed (ΔV_{85}).

3. Literature Review

As per the report of Indian Ministry of Road Transport and Highways (MoRTH, 2016), National Highways constitute 2.9 percent of total road network accounting 29.6 percent of accidents and 25.3 percent of the accidents contributed by State Highways. Statistical data from National Highways Authority of India (NHAI, 2017) shows that the 51 percent of the total National Highways road network are of two-lane standards. Various studies are conducted to analyse and model the consistencies and inconsistencies of the highway geometric designs. Lamm et al. (1988) identified 11 spots from the beginning of the curve into the approach tangent. Spot speeds at the identified spots were recorded by the researcher using voice recorder device looking at the odometer while travelling in the vehicle. To have the variation in the samples, follow and test car method was adopted. The study confined to the passenger cars and assumed that entire acceleration and deceleration of vehicles takes place on the tangent and speed remains constant on the horizontal curves. 85^{th} percentile speed models were developed for operating speed on the curve and the tangent. Acceleration and deceleration rates were found to be 0.85 m/s^2 and 0.88 m/s^2 respectively. The design proposal was based on tangent as the non-independent design element and independent design element based on the reduction in speed and availability of tangent between the curves. Andueza (2000) studied design inconsistency for mountainous terrain which included 21 curves and 18 tangents. Spot speed data was collected for the passenger cars using radar gun. Speed and comfort were found to be two significant factors while traversing from tangent-to-curve. The driver has to sacrifice comfort to maintain the same speed as on tangents while traversing the curve leading to the safety issue and if the driver emphasizes on comfort, then there will be a reduction in speed from the tangent-to-curve. Models were developed for the average and 85^{th} percentile operating speed on the tangent and the curve. Super elevation was found statistically insignificant for the developed operating speed models. However, the curve radius and previous curve radius were found to be statistically significant influencing factors for the development of operating speed model on the curve and tangent respectively. Authors also found that in the case of short tangents, speeds are found to have a linear relationship with the tangent length. Misaghi & Hassan (2005) developed models to check the design consistency using electronic counters/classifiers at the beginning of curve, mid-curve, end of the curve, approach tangent and departure tangent. Results showed that the passenger cars and trucks have similar operating speed and speed differential values and can be classified as one vehicle type. The relatively weaker relationship developed for ΔV_{85} and stronger relationships for $\Delta_{85}V$. Castro et al. (2011) used radar meters and radar operators to measure the spot speed for passenger cars. Speed data were collected at specific locations on the tangent and the curve portion. It was found that the vehicle speed at the beginning, midpoint, and the end of the curve depend on the curve length and deflection angle and in some cases on the approach tangent. Jacob & Anjaneyulu (2012) developed operating speed and speed reduction models for different classes of vehicles (Car, Two-wheeler, Bus, Truck, and the combination of all). Operating speed and speed reduction found to differ based on the road geometry for different vehicle classes. The operating speed of the buses was found to be more sensitive to curve length than the radius. Maji and Tyagi (2018) developed speed prediction models for four lane divided highways. Models were developed different vehicle types (car, light and heavy commercial vehicles) at midcurve, point of curvature and 50 m prior to point of curvature. The study revealed that curve length could be important factor in the geometric design procedure. Nama et. al. (2016) investigated geometric design consistency on mountainous terrain using existing evaluation methods. Radar gun was used to collect speed for cars and trucks. The study was conducted on four lane divided national highways for distinct horizontal and vertical alignment features. Authors observed that 79 % and 93 % locations exhibit good level of consistency as per Lamm's criteria I and II. They also concluded that average vehicle operating speed at most of the cases exceeds design speed. Montella et al. (2014) used the instrumented vehicle and driving simulator to develop the operating speed and acceleration/deceleration models for four-lane rural highways. The study showed that 52% of the drivers began to decelerate in approach tangent and ends in a curve for radius lesser than 400 m and even the same for radius greater than 400 m. Acceleration started in the curve for 90% of the transitions and in 27% cases acceleration began before the first half of the curve, and the rest began in the second half of the curve. The study results showed that individual 85th percentile driver's speed reduction was greater than the operating speed reduction of the drivers. The study also concluded that the longitudinal downgrade has the significant effect on acceleration but not on the deceleration. Montella et al. (2014) studied design inconsistency using the driving simulator. The results revealed that the 85th percentile speed reduction from tangent-to-curve by individual drivers was two times greater than the operating speed difference from tangent-to-curve. They also concluded that acceleration and deceleration rates for the individual drivers were approximately two times greater than the acceleration and deceleration rates used to draw speed profiles. Llopis-Castelló et al (2018) used pocket sized GPS device to collect continuous data for loaded and unloaded trucks. The grade at the point of the curvature and the radius of the horizontal curve have significant influence on the operating speed of heavy vehicles. Authors also concluded that operating speed at the midpoint of the curve and minimum operating speed are not the same.

In summary, quite a few Studies have been conducted on two-lane rural highways confined to passenger cars using instrumented vehicle (Nie & Hassan 2007; Zuriaga et al. 2010; Memon 2012; Bella 2013; Montella 2013; Pérez-Zuriaga 2013). However, studies are not available in India for heavy vehicles for developing speed prediction models using continuous speed trajectory. The advances in the technology enabled to collect continuous speed data using GPS to develop more reliable operating speed models. Therefore, in the present study GPS data was used to develop speed differential model for heavy vehicles.

4. Data Collection

Data collection for the continuous speed measurements were conducted in the states of Telangana and Karnataka, India. The GPS data logger device (10 Hz) and the video camera was mounted on the windshield and side window glass of the heavy vehicles respectively for continuous speed profile measurements. In the present study, speed measurements were taken for MDR and SH, the details of selected stretches are shown in Table 1. The details of highway geometric design elements for MDR and SH are tabulated in Table 2 and Table 3. The data for MDR was collected from October to December 2017 between 10.00 a.m. to 1.00 p.m. during daytime under dry weather conditions on working days for three months. 15 buses and 17 male drivers were chosen to study the driving behavior along the MDR stretch to evaluate the design consistency. The drivers aged between 22 to 46 years with professional driving experience and license issued for heavy motor vehicle driving from the government of India were involved in the study. The data collection was further extended to state highways between April and May 2018 from 10:00 a.m. to 1:00 a.m. on the working days for two months. In total, the data was collected for five months for naturalistic driving study to evaluate design consistency. The device was mounted on express and luxury government buses at one end of the bus terminal and unmounted on the other terminal end for SH. The selected stretch has no major settlements and low enough traffic volume with headway greater than 5s which enabled to obtain significant samples operating at free-flow conditions. There were no stops between the two major terminals of the selected stretches which made it possible to collect significant samples without any interaction affecting the driver behavior concerning geometry. Moreover, the data collection was carried out for express buses with stops at major terminals. The age of the drivers ranging between 26 to 57 years with professional driving experience were included to trace operating speed of the heavy vehicles on successive geometric design elements of SH. The heavy vehicles used for data collection for MDR and SH are represented in Fig. 1.

Table 1. Road segment characteristics.

Alignment features	Two lane rural highway segments	
	MDR	SH
Alignment length (km)	10.99	31.21
Number of curves	12	17
Radius of horizontal curves	40 to 2000	50 to 1000
Deflection Angle(degree)	11 to 74	9 to 95
Horizontal curve length (m)	23.97 to 535.13	36.15 to 222.49
Degree of Curvature (m)	0.57 to 38.19	1.14 to 22.91
Chord length (m)	23.34 to 533.53	35.37 to 214.53
Number of observations	61	40
Number of different drivers	17	40
Paved Shoulder	NA	NA
Gradient	<4%	<4%

Table 2. Site geometric details for MDR

Sr.No	Radius (m)	Deflection Angle	Curve Length (m)	Degree of Curvature (◦)
1	80	74° 02' 24.46"	103.38	14.32
2	60	40° 35' 30.25"	42.51	19.10
3	60	49° 05' 01.18"	51.40	19.10
4	200	22° 24' 08.42"	78.20	5.73
5	100	46° 38' 02.25"	81.39	11.46
6	1000	17° 58' 06.81"	313.61	1.150
7	2000	15° 19' 49.41"	535.13	0.57
8	600	13° 06' 30.82"	137.27	1.91
9	800	21° 25' 05.14"	299.05	1.43

10	600	12° 10' 50.21"	127.56	1.91
11	80	30° 28' 32.21"	42.55	14.32
12	70.000	60° 00' 30.91"	73.31	16.37

Table 3. Site geometric details for SH

Sr.No	Radius (m)	Deflection Angle	Curve Length (m)	Degree of Curvature (◦)
1	60	59° 09' 02.78"	61.94	19.10
2	1000	08° 35' 59.03"	150.09	1.15
3	125	47° 07' 46.25"	102.82	9.17
4	200	30° 14' 16.30"	105.55	5.73
5	240	53° 05' 46.83"	222.41	4.76
6	200	18° 29' 58.62"	64.58	5.73
7	150	40° 24' 12.09"	105.78	7.64
8	300	24° 07' 15.91"	126.30	3.82
9	170	36° 03' 50.21"	107.00	6.74
10	800	09° 49' 55.78"	137.28	1.43
11	130	27° 09' 07.04"	61.61	8.82
12	90	40° 32' 34.32"	63.69	12.73
13	240	16° 30' 40.99"	69.16	4.77
14	170	50° 55' 35.68"	151.10	6.74
15	200	43° 52' 57.55"	153.18	5.73
16	240	23° 48' 54.63"	99.76	4.78
17	360	20° 00' 03.88"	125.67	3.18
19	140	35° 01' 50.66"	85.60	8.16

The high-end GPS data loggers were installed in the subject vehicle; the device was monitored by the research student who travelled in the same vehicle. The questionnaire survey was conducted at the beginning of every trip which included the details of driver such as name, age, experience, full-time occupation, desired driving speed, any accidents on rural highways, and cause for it. The speed profile data for the state highway were unique for every sample, i.e. no driver is repeated, and such repeated samples are discarded from the study. The video data collected were processed for spot speed measurements at specific locations to ensure that the naturalistic driving behavior of the driver was not affected due to the presence of GPS device.

a

Fig.1. Heavy vehicles used for data collection (a) MDR (b) SH

5. Data Reduction

The data collected using the GPS device has speed measurements at every 0.1 seconds with temporal and spatial coordinates. Highway design and data mining software's were used to split the data into preceding tangent, horizontal curve, and succeeding tangent segments for further analysis as shown in Fig. 2.

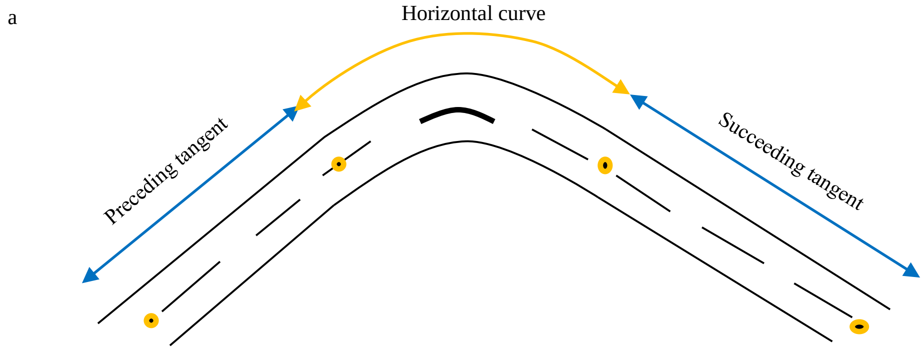

Fig. 2. Representation of tangent and horizontal Curve

The complete trajectory of every sample collected was generated in the design software and thoroughly analyzed for tangent and curve segments to check the GPS data missing due to the signal problem. The samples with missing data due to weak signal at any tangent-to-curve/curve-to-tangent segment were discarded for that particular tangent-to-curve segment. Of the total data, two samples for MDR and one sample for SH were removed due to weak signal. The speed data affected due to the presence of the lead vehicle, overtaking the vehicle, head on vehicle, and cattle crossing at specific locations were marked on trajectory and data was trimmed at such locations. The effected tangent to curve as well as the succeeding tangent-to-curve was removed from the analysis. The urban area at the bus terminals to the beginning of the rural highways on both terminals were trimmed from the study so as to represent the significant data only for rural highways.

6. Model Development

Regression tool was used to develop the operating speed models with various geometric elements as the independent variables. The geometric variables considered in the study as explanatory variables includes radius (R), deflection angle (Δ), curve length (Lc), and tangent length (Lt). The statistical significance of the developed regression models was set at 95 percent confidence level ($p < 0.05$).

The preliminary correlation analysis was carried out to study the relationship between speed and geometric variables. Radius and preceding tangent length found to have a strong positive correlation with speed reduction. Radius showed a negative correlation co-efficient value of 0.72 and preceding tangent length of 0.60 with speed reduction from tangent-to-curve. However, other variables found to have a correlation co-efficient value less than 0.4. Step-wise linear and multiple linear regression was carried out to study the relationship with different explanatory variables. Radius and preceding tangent length found to explain strong association with speed reduction at 95 percent confidence level. Hence in the development of speed differential model radius and preceding length were considered. The $\Delta_{85}V$ model developed with radius and preceding tangent length as independent variables is given by equation 1.

$$\Delta_{85}V = 14.2387 - 0.0189R + 0.0074P_{TL} \tag{1}$$

Where, $\Delta_{85}V$ = 85th percentile operating speed differential; R = radius; and P_{TL} = preceding tangent length. The statistical analysis results of the developed model are tabulated in the Table 4. The resulting R^2 value of the proposed model was 0.70 with $t - statistic$ = 5.10, and the coefficient was significant at the 95% confidence interval. The coefficient of the independent variable significantly different from zero at the 95% confidence interval. The negative and significant co-efficient R indicates that drivers tend to show larger speed variation as the radius decreases. Drivers attain higher speeds as the length of the tangent increases and sudden decrease in speed due to small radii. Hence, the positive and significant P_{TL} shows that drivers show speed reduction from tangent-to-curve as the tangent length increases.

Table 4. Statistical summary for developed model

Parameter	Estimate	Standard Error	t-statistic	p-value	R^2	R^2_{adj}
Constant	14.24	2.79	5.10	0.00	0.70	0.65
Radius (R)	-0.02	0.01	-3.92	0.00		
Preceding tangent length (P_{TL})	0.01	0.01	2.71	0.02		

The 85th percentile speed distributions of operating speed on the tangent and curve may not remain the same for both elements for the same driver as per Hirsh (1987). Hence the approach of calculating the 85th percentile speed reduction by simple subtraction is not valid. One of the drawbacks of using spot measurements was difficulty involved in finding out the exact position where the driver starts and ends the deceleration. Apart from that, it is also necessary to understand on which geometric element, i.e., on either tangent or on the curve, the driver starts and ends deceleration. To overcome these drawbacks, GPS data logger was mounted on the heavy vehicles to trace the continuous speed measurements at every 0.1s. In the current study, $\Delta_{85}V$ was calculated for each driver sample and on every tangent-to-curve transition by taking 85th percentile speed difference on tangent-to-curve. Furthermore, ΔV_{85} defined as the simple subtraction of the 85th percentile operating speed on the tangent and operating speed on curve irrespective of the driver sample for every transition for both elements was calculated. The relationship between $\Delta_{85}V$ and ΔV_{85} was developed and is given by equation (2) from Fig. 3.

$$\Delta_{85}V = 2.5794 + 1.2781\Delta V_{85} \tag{2}$$

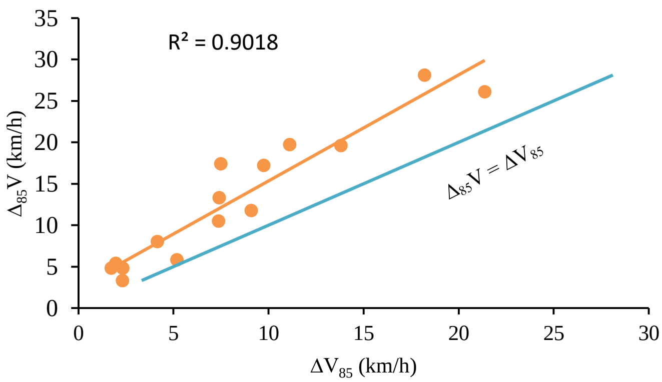

Fig. 3. Relationship between $\Delta_{85}V$ and ΔV_{85}

Based on equation (2) and Fig .3, it can be observed that intercept of equation (2) is approximately 3km/h greater than $\Delta V_{85} = \Delta_{85}V$. Hence it can be concluded that ΔV_{85} underestimates the $\Delta_{85}V$ by approximately 3km/h for heavy vehicles. The $\Delta_{85}V$ variation from tangent-to-curve for different radii are plotted as shown in the Fig. 4. To show the continuous variation of the speed, different curves with radii <100 m, 100 – 200 m, 200-300 m, and ≤ 400 m are selected and depicted in Fig. 4. The output of the GPS data logger having average speed fluctuations ≤ ± 2-3 km/h are smoothened by smoothing spline function using data mining software. All the tangent-to-curve transitions for different radii are brought to common scale and are represented in Fig. 5. It can be shown from Fig. 4 and Fig. 5 that the maximum speed reduction was found to be 26.10 km/h on 60 m radius and minimum on 400 m with 4.828 km/h. For a radius of 60 m the speed reduction is 26.10 km/h, for curve radius of 90 m the speed reduction was slightly lesser which is around 19.63 km/h, and the speed reduction is approximately around 17.25 km/h for a radius of 150 m. The speed reduction further drops to 10.52 km /h and 8.05 km/h for radii of 170 m and 24 m respectively. The values in the speed reduction clearly indicates that speed reduction decreases as the radius increases. In case of radius with 60 m, and 90 m the symmetry in the speed reduction on the preceding and succeeding tangent is not found because of longer approach tangent followed by shorter departure tangent whereas in case of the curve of with radius 240 m it is shorter preceding tangent followed by longer succeeding tangent. Besides, the speed reduction will be more for sharp curves followed by a longer preceding tangent length. The speed variation from tangent to the curve should not be more than 10 kmph (AAD, T. 1988; Dhahir & Hassan 2019) as to promote the sudden deceleration resulting in risk of getting into an accident and therefore compromising safety and comfort of both driver and passengers. The speed reduction model will be helpful for the designers to identify the locations with larger speed variation at the time planning, or reconstruction/realignment projects.

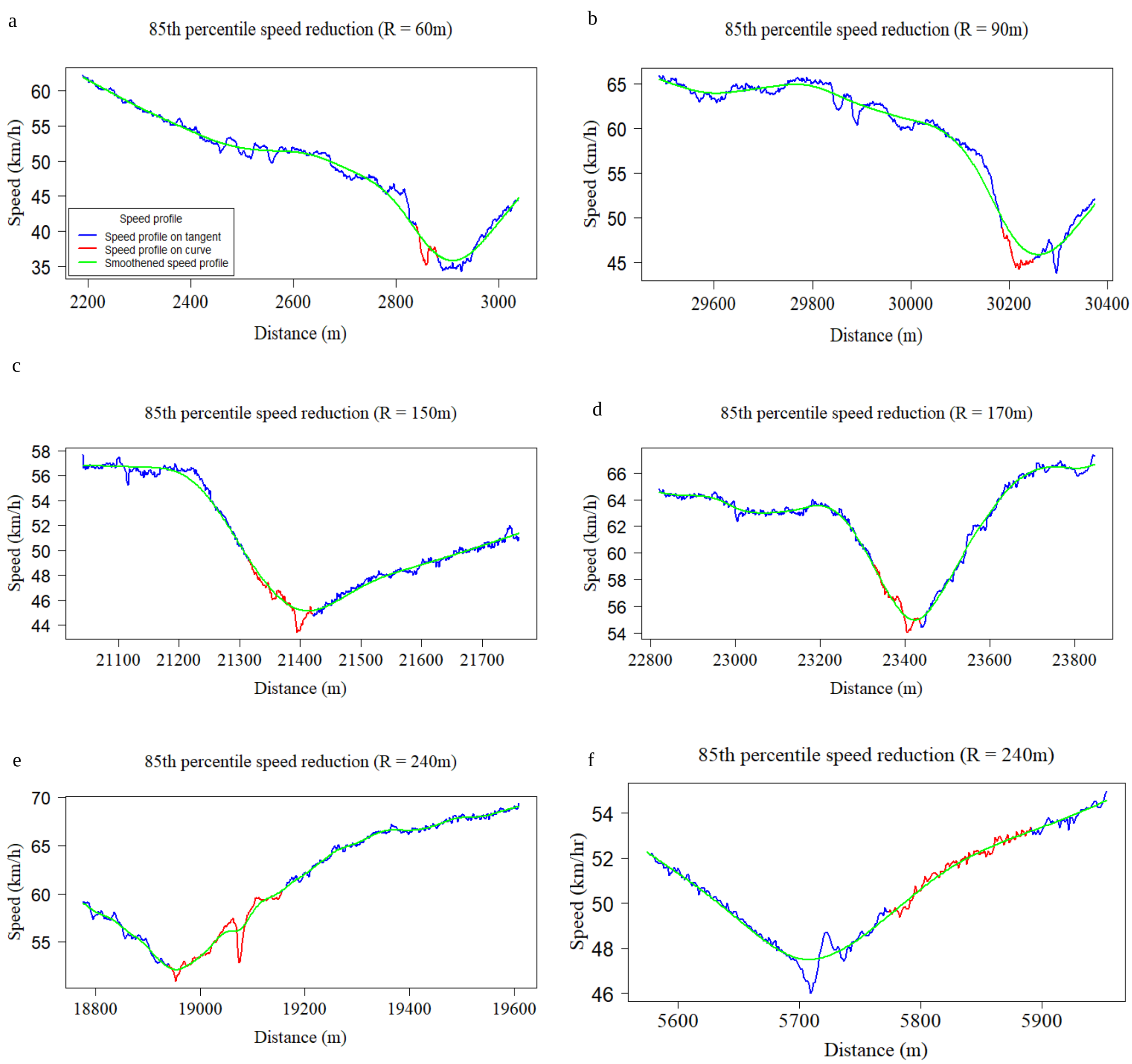

Fig. 4. 85th percentile speed reduction graphs for different radii

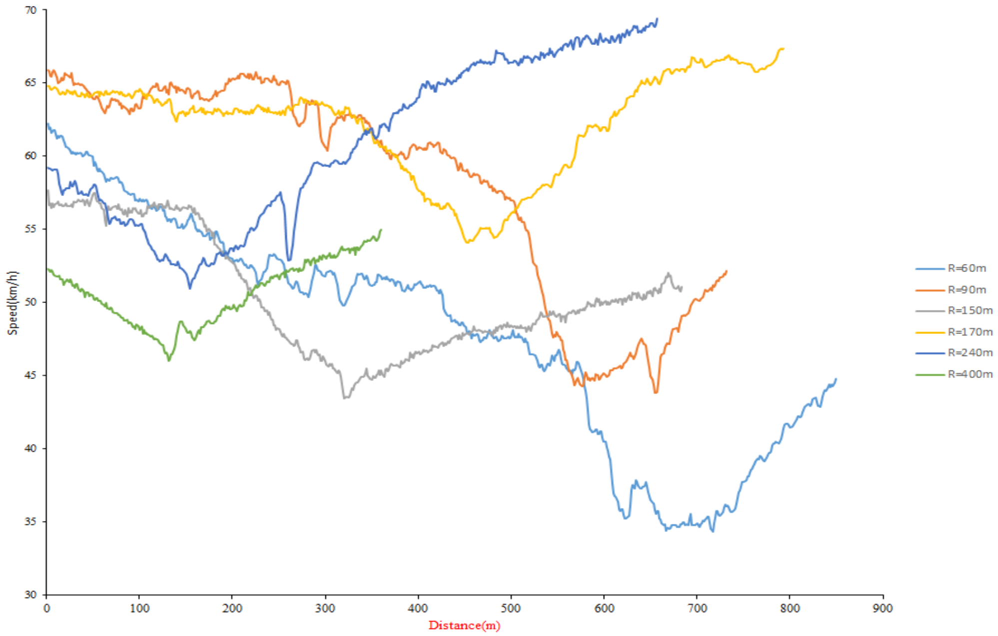

Fig. 5. Tangent to curve variation in speed for different radii

7. Conclusions

The research presents the analysis results of naturalistic driving behavior on rural highways for heavy vehicles in the states of Telangana and Karnataka, India. The device was mounted on the heavy vehicles and a total of 83 and 40 samples were collected for MDR and SH respectively. The GPS device made it possible to trace the continuous operating speed variation from tangent-to-curve and to trace the beginning and end points of deceleration of the vehicle along the tangent-to-curve. 85th percentile operating speed differential model was developed and independent variables such radius, deflection angle, degree of curvature, curve length, preceding tangent length, and succeeding tangent length were studied and analyzed. However, radius and preceding tangent length were found to statistically significant for the development of multiple regression model to evaluate the highway design consistency with respect to driver's expectations. Further a relationship was established between $\Delta_{85}V$ and ΔV_{85}. Models developed based on ΔV_{85} underestimates the actual speed reduction caused by $\Delta_{85}V$ and $\Delta_{85}V$ is 3 km/h lower than ΔV_{85} for heavy vehicles. Multiple regression model developed for $\Delta_{85}V$ found to be dependent on preceding tangent length and radius of the curve. With the increase in preceding tangent length, $\Delta_{85}V$ found to increase and decrease with an increase in radius. The symmetry in speed profile is not observed for curves with radii 60 m and 90 m because of longer preceding tangent followed by shorter succeeding tangent. However, in case of the curve with radius 240 m it is opposite of 60 m and 90 m radius. Hence it concludes that preceding tangent plays significant role in the amount of speed reduction from tangent curve. The attainment of free flow speed depends on the length of tangent available which affects the symmetry in speed reduction from tangent-to-curve and curve-to-tangent. The minimum radius found to be 60 m with maximum speed reduction of 26.04 km/h on it and 17.36 km/h on 300 m radius. The speed reduction for 400 m curve was found to be 4.83 km/h which falls in good design as per Lamm's criteria I.

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