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Geometric design consistency of multiple horizontal curves on two-lane rural highways

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Abstract

Safety on rural highways is of great concern as nearly two third of road fatalities are found to take place on such roads. High speed of vehicles is the characteristic of rural highways. Geometry is one of the factors that control the speed of vehicles and consequently, the crash occurrence. Alignment is one of the components of geometry and an abrupt change in the alignment is a leading cause for crashes in rural highways. Presence of a curve after a long tangent or a sharp curve after a flat curve is an example for inconsistency in the alignment. Such an alignment brings about unnecessary and unhealthy speed changes that may lead to crashes. Thus, a highway design can be evaluated based on consistency in geometry. Operating speed is the measure adopted for consistency evaluation in this study.

The objectives of this study are to develop operating speed models for different classes of vehicles at salient locations of multiple horizontal curves and to develop criteria for evaluating the geometric design consistency. Data of 30 sites were made use for this purpose. Multiple linear regression technique was adopted for modelling. Models were developed for the tangent section and middle of curved sections. Length of preceding tangent is the variable influencing operating speed at tangent. Radius and length of curve significantly influence operating speed at middle of first curve and radius of first and second curve influences operating speed at middle of second curve. Operating speed Deviation from Design speed (ODD) and Speed Reduction (SR) are the consistency measures and Equivalent Property Damage Only (EPDO) crashes is the safety measure used in the study for developing criteria. The criteria developed can be used to evaluate the curve as a single element, and as successive elements (combinations of tangent/curve or curve/curve). Alignment can then be classified as Good, Fair or Poor using these criteria, and it helps a designer to make suitable modifications in the design of a multiple horizontal curve from safety point of view.

Selection and peer-review under responsibility of International Scientific Committee.

Keywords: Multiple horizontal curve; Operating speed; Speed reduction; Design consistency criteria

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1. Introduction

As per the World Road Statistics (2008) report of International Road Federation, India is the major contributor to road crash fatalities. About two-third of the fatalities that takes place in India is on National Highways and State Highways, in rural areas. Vehicles in rural highways are less interrupted by other vehicles and drivers are able to move at their desired speed, permitted by the geometry of road. Studies showed that more than 50% of fatal crashes in rural highways take place at curves (Lamm et al., 1992). This happens when a driver encounters with an unexpected change in alignment along a highway. Many studies underlined the relationship between crashes and curve geometry (Johnston, 1982, Bhatnagar, 1994, Lamm et al., 1994). Hence, a good design of highway geometry necessitates proper coordination of straight and curved sections, so that drivers will not be surprised by a change in the alignment. In other words, any improper design of geometry leads to unnecessary speed changes. If this variability in speed demanded by the geometry is beyond safe limits, the driver may take on an inappropriate manoeuvre. As speed on highways is comparatively high, any erroneous driving manoeuvre may result in crashes of high severity. Such a road design is generally considered to be inconsistent.

Evaluating the consistency of geometric design is one of the promising strategies for improving the rural highway safety as sections that lack design consistency experience high collision occurrences (Krammes, 1997). The available methods for evaluating consistency are speed based, vehicle stability based, alignment indices based and driver workload based (Fitzpatrick et al., 2000). Among the available methods, operating speed based approach can be reckoned as the most efficient and widely used. This is because speed is a visible indicator of consistency (Nicholson, 1998). Also, operating speed and speed variations can be easily observed and measured.

Estimation of operating speed from highway geometry is the first step in the consistency evaluation process. Models are developed by many researchers to quantify the relationship between speed and geometry. Given the roadway characteristics of a highway alignment feature, operating speed on the feature can be predicted using such models. But Misaghi and Hassan (2005) reported that models developed in different countries by various researchers vary in their model form, model parameters and the influencing variables. Among the various geometric features, influence of single horizontal curves on operating speed has been a major subject matter of research. Also, most of the models developed are for predicting the operating speed of passenger car. Anitha and Anjaneyulu (2013) developed models for predicting operating speed of different classes of vehicles for Indian traffic condition at single horizontal curve and its preceding tangent. The influencing variables identified by them are length of curve, radius of curve and length of tangent.

Limited work has been done on deriving criteria for consistency evaluation. Lamm et al. (1999) proposed criteria to evaluate single element (Single horizontal curve) and successive elements (tangent/curve) as given in Table 1. They related operating speed based consistency measures to crash rate to derive the threshold values. Design can be classified as Good, Fair and Poor. Very few studies explored the scope for evaluating multiple horizontal curves based on operating speed.

Table 1. Design consistency evaluation criteria by Lamm et al. (1999)

	Single Element	Successive Elements
Good Design	$\lvert V_{85} - V_D \rvert \leq 10 km/h$	$\Delta V_{85} \leq 10$ km/h

Fair Design	$10 < \lvert V_{85} - V_D \rvert \leq 20 km/h$	$10 < \Delta V_{85} \leq 20$ km/h
Poor Design	$\lvert V_{85} - V_D \rvert > 20 km/h$	$\Delta V_{85} > 20$ km/h

where, V_{85} is the operating speed and V_D is the design speed at a curve. ΔV_{85} is the deviation of operating speeds at tangent and midcurve sections.

The objectives of this paper are twofold. The first part of the paper proposes models for predicting operating speeds of different classes of vehicles at multiple horizontal curves. The second part derives criteria for evaluating consistency of multiple horizontal curves.

2. Data description

Data requirement include geometric data, speed data and crash data. Details regarding geometry and speed are necessary for developing speed prediction models. Crash data help to derive evaluation criteria. Data of 30 sites with multiple horizontal curves were selected from various two-lane rural highways in Kerala state of India. Among these 27 were reverse curves. The following criteria were adopted while selecting the sites.

No stop-controlled or signalized intersections nearby.
Not located close to towns or built up areas that may significantly affect the speed patterns on the curves.
Marked and paved roadway.
A minimum tangent length of 100 m on a flat terrain prior to the first curve.
Good pavement condition.

The geometric data collected for each curve in the series include direction of curve, radius, and length of curve, degree of curvature, deflection angle, superelevation, width of carriageway and width of shoulder. In addition to the above data, the length of the preceding tangent was measured for the first curve in the series. Summary statistics of the geometric data are given in Table 2.

Table 2. Summary statistics of geometric variables

	Curve 1								Curve 2						
	PTL (m)	Radius (m)	LH (m)	DC (deg)	DA (deg)	CW (m)	SW (m)	e (%)	Radius (m)	LH (m)	DC (deg)	DA (deg)	CW (m)	SW (m)	e (%)
Minimum	100	25	33	2.5	5.5	5.7	0.1	0.7	41	29	2.5	5.5	5.7	0.2	0.1
Maximum	463	701	162	69.9	128.8	12.2	2.8	8.8	701	190	42.6	106.5	10.5	2.9	11
Average	161	149	67	19.8	40.7	8.0	1.4	4.2	185	74	14.4	33.2	7.7	1.6	4.2
Standard Deviation	78	134	29	14.7	28.2	1.7	0.7	2.2	139	40	9.0	25.4	1.4	0.8	2.6

The classified speed data of vehicles moving along the curves were collected manually for about six hours at each of the sites. Around 300 observations were taken. The spot speed observation locations for a typical reverse curve are shown in Fig 1. Here, AT is the location on the approaching tangent 60 m before the beginning of first curve. PC_1 and PC_2 are the beginning and PT_1 and PT_2 are the end of first and second curves, respectively.

Similarly, MC_1 and MC_2 are the midpoint of first and second curves. Speeds of different classes of vehicles like two wheeler, car, bus and truck were collected manually using digital stop watch of 1/100 seconds accuracy. Enumerators noted down the vehicle registration number along with the type of vehicle and time taken by the vehicle to travel a known trap length at each of the observation locations. Only free flowing vehicles were considered.

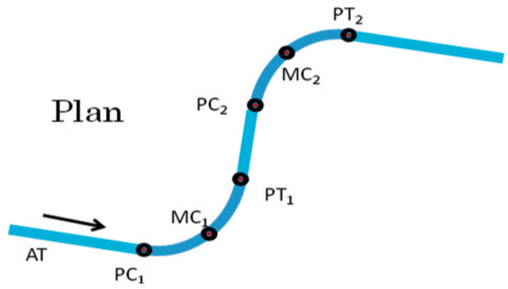

Fig 1. Spot Speed Observation Locations for Reverse Curve

The source of crash data was the first information report of police records. The data included location, type of vehicles involved and severity of crash. The number of crashes that took place at each site was identified. Crashes of different severity were then normalised using crash severity indexing method. An Equivalent Property Damage Only crashes (EPDO) was calculated for each site after giving weights of 1, 4 and 12 for property damage only crashes, injury crashes and fatal crashes, respectively. These weights were arrived at based on a study conducted on insurance claims given to various types of crashes by the insurance companies in the state.

3. Data analysis and model development

3.1. Preliminary analysis

Analysis of Variance (ANOVA) was done to check whether speeds of different classes of vehicles are significantly different or not. The results of the tests showed that, in majority of the cases, there is no statistically significant difference between the speeds of bus and truck. Hence, these two classes are grouped together and named as heavy vehicle. However, in nearly all cases, there is statistically significant difference between the speeds of passenger car, two-wheeler and heavy vehicles at 5% level of significance. Finally, the three classes of vehicles identified for further analysis are passenger car, two-wheeler and heavy vehicles. Analysis was done for all vehicle categories also. Operating speed for each class of vehicle is calculated as the 85th percentile of spot speed observations. Similarly, 85th percentile of speed difference from tangent to first curve and first curve to second curve were also estimated.

3.2. Development of operating speed model

Models for predicting operating speed at tangent (AT) and middle of first curve (MC1), taken from the work of Anitha and Anjaneyulu (2013), are given in Table 3. Operating speed at tangent is influenced by length of preceding tangent up to speed observation (PTLS) and operating speed at middle of first curve is influenced by length and radius of curve. Operating speed models for multiple horizontal curves at middle of second curve are developed using data of 20 sites. Data of 10 sites were used for validation. The various independent geometric variables tried are the radius (R), carriageway width (CW), shoulder width (SW), length of curve (CL), deflection angle (Δ), degree of curve (DC) and super elevation (e). Model validation was done based on the %RMSE values. Models with less %RMSE are finally selected. The variables that influence the operating speed at second midcurve section are the radius of the first and second curve, R_1 and R_2 respectively. The final models selected are given in Table 4. All the models are statistically significant. Coefficients of all the constants and variables are significantly different from zero at 95 % confidence level.

Table 3. Models for Operating Speed at Tangent Section

Vehicle Type	Tangent section	R^2	Midcurve section of first curve	R^2
Car	$V_{85AT} = 47.50 + 3.6 \times PTLS^{0.312}$	0.89	$V_{85MC1} = 69.00 - \frac{1005.39}{R} - 0.065 \times CL$	0.80
Two Wheeler	$V_{85AT} = 44.10 + 3.6 \times PTLS^{0.300}$	0.87	$V_{85MC1} = 67.00 - \frac{1105.72}{R} - 0.069 \times CL$	0.82
Bus	$V_{85AT} = 45.00 + 3.6 \times PTLS^{0.281}$	0.90	$V_{85MC1} = 70.20 - \frac{1169.68}{R} - 0.099 \times CL$	0.83
Truck	$V_{85AT} = 37.50 + 3.6 \times PTLS^{0.335}$	0.95	$V_{85MC1} = 63.20 - \frac{1063.82}{R} - 0.061 \times CL$	0.84
All Vehicle	$V_{85AT} = 45.00 + 3.6 \times PTLS^{0.312}$	0.91	$V_{85MC1} = 65.00 - \frac{1009.90}{R} - 0.053 \times CL$	0.86

Table 4. Operating Speed Models for Midcurve of Second Curve

	Model	*t-values*			R^2	R_a^2	*%RMSE*	
		Constant	R_1	R_2			*CD*	*VD*
Car	$V_{85MC2} = 74.87 - \frac{145.47}{\sqrt{R_1}} - \frac{145.09}{\sqrt{R_2}}$	*9.67*	*2.36*	*4.147*	*0.51*	*0.45*	*5.08*	*6.69*
Two-wheeler	$V_{85MC2} = 60.80 - \frac{103.88}{\sqrt{R_1}} - \frac{84.54}{\sqrt{R_2}}$	*9.59*	*3.61*	*1.685*	*0.43*	*0.37*	*4.15*	*5.83*
Heavy Vehicle	$V_{85MC2} = 73.35 - \frac{151.57}{\sqrt{R_1}} - \frac{158.78}{\sqrt{R_2}}$	*10.10*	*4.64*	*2.784*	*0.57*	*0.52*	*4.72*	*9.67*
All Vehicle	$V_{85MC2} = 71.94 - \frac{144.78}{\sqrt{R_1}} - \frac{130.37}{\sqrt{R_2}}$	*10.35*	*4.59*	*2.370*	*0.56*	*0.50*	*4.56*	*7.82*

CD – Calibration Dataset VD – Validation Dataset

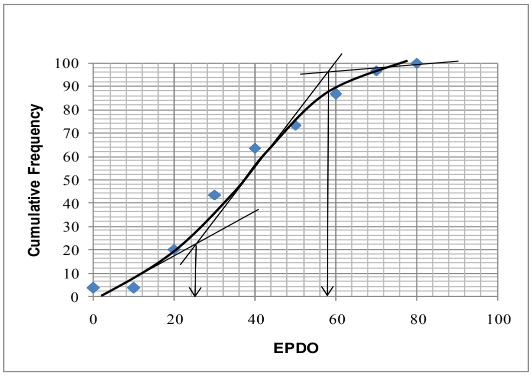

Fig 2. Cumulative frequency diagram of EPDO

4. Development of consistency evaluation criteria

A design is said to be up to the expectation of a driver, if the speed with which one drives is at par with the speed for which the alignment component is designed (Single element approach). Similarly, operating speed deviation from one component to the other, such as tangent to a curve or from first curve to second curve has to be within safety limits (Successive elements approach). Thus, by comparing operating speed with design speed and operating speeds between adjacent sections, a designer can check whether a design is consistent or not. In this study, EPDO crash value is categorized as less, medium and high based on the trend observed in the cumulative frequency diagram as shown in Fig 2. EPDO value less than 30 is *less*, between 30 and 60 is *medium* and more than 60 is *high*. For each site, EPDO value was compared with the operating speed measure for consistency. Analysis was done for both single element and for successive elements for All Vehicle category.

4.1. Single element

Operating speed Deviation from Design speed (ODD) is the consistency measure used to evaluate single element. Greater the speed difference, greater will be the design inconsistency and therefore there is more chance for crashes. Equation 1 is used for estimating design speed. VD is the design speed in km/h; R is the radius of curve in m; e is the rate of super elevation (%); f is the coefficient of lateral friction = 0.15.

$$V_D = \sqrt{127R(e+f)} \tag{1}$$

To develop the criterion, ODD was calculated for the midcurve of first curve. A grid of ODD and EPDO was generated as shown in Fig 3 and each site was located in this grid based on its ODD and EPDO. The scatter obtained was visually scrutinized. EPDO values are found to increase with increase in the value of ODD. Three different clusters were observed from the grid. Among the different boundary values possible for each cluster, the best ones were selected by conducting ANOVA test. The grouping which is having minimum variance within the clusters and maximum variance between the clusters was selected from the test. Table 5 shows the results of ANOVA test conducted on some of the trials. The criterion selected for single element is given below.

ODD ≤ 10 km/h - Good design
10 < ODD ≤ 20 km/h - Fair design
ODD > 20 km/h - Poor design

Table 5. Results of ANOVA Test for Selection of Consistency Measure Classification

Trial	Consistency Thresholds (km/h)	F_{CAL}	F_{TAB}
1	< 10 10-20 >20	6.38	3.35
2	<8 8-16 >16	1.73	3.35
3	<12 12-20 >20	1.73	3.35

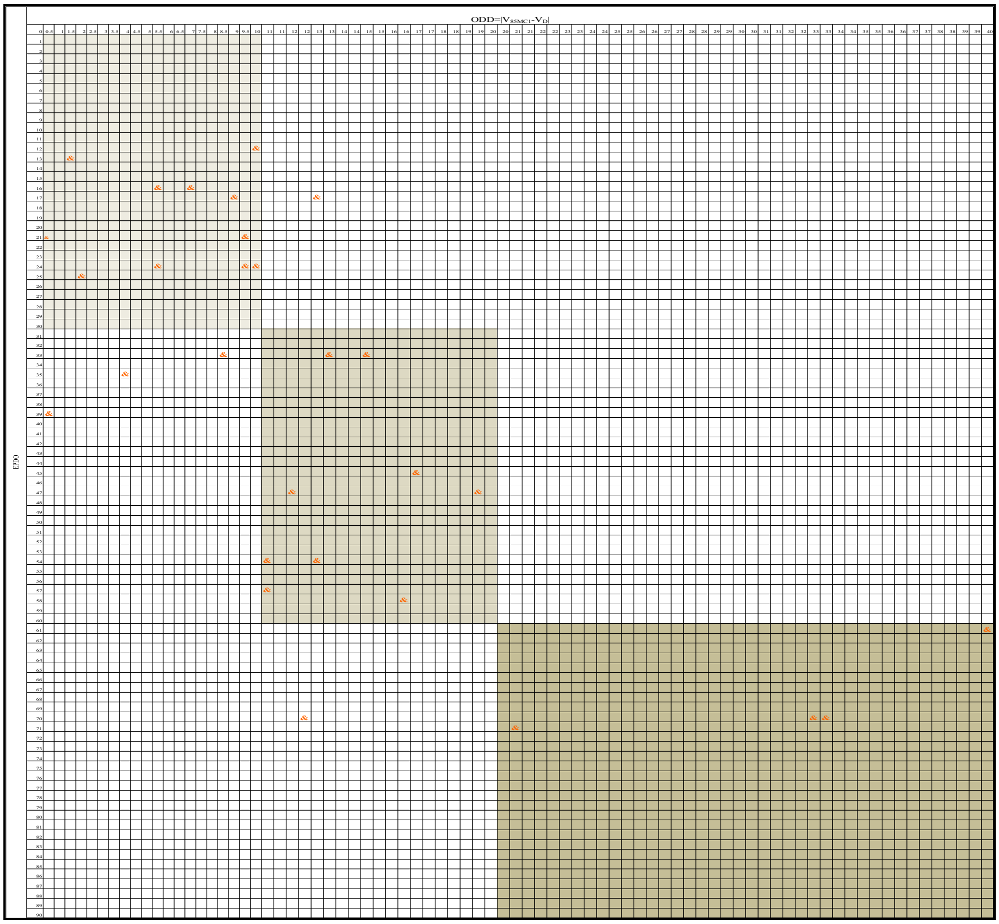

Fig 3. ODD – EPDO grid for single element

4.2. Successive elements

For successive elements two types of consistency evaluation criteria were developed. First criterion is based on speed reduction from approach tangent (AT) to first mid-curve section (MC_1). It is represented as (SR_{AT-MC1}). Second is based on speed reduction from middle of first curve (MC_1) to the middle of second curve (MC_2). It is represented as ($SR_{MC1-MC2}$). 85th percentile of speed reduction was used for the analysis. Fig 4 and Fig 5 show the grids for these two measures. It can be observed that the more the speed reduction from one component to the other, the more is the EPDO value. The criterion selected for evaluating the tangent/curve combination and curve/curve combination is given in Table 6.

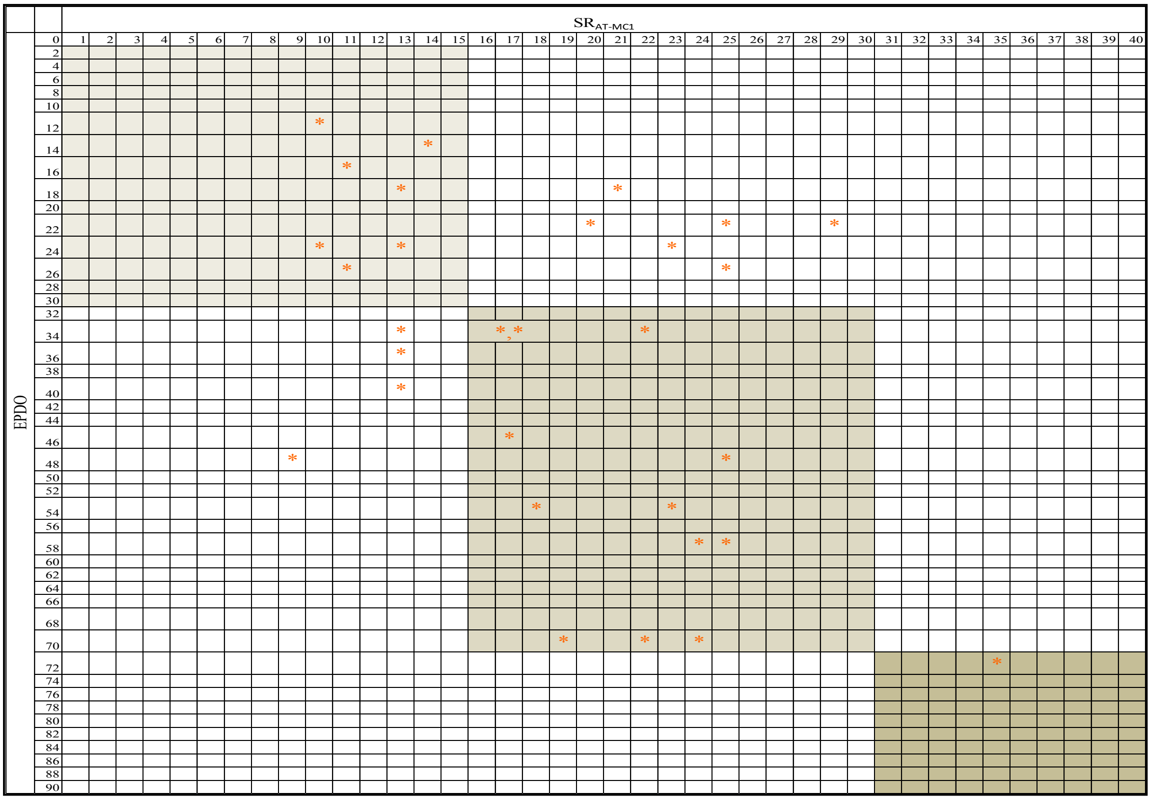

Fig 4. SR-EPDO grid for Tangent/Curve combination

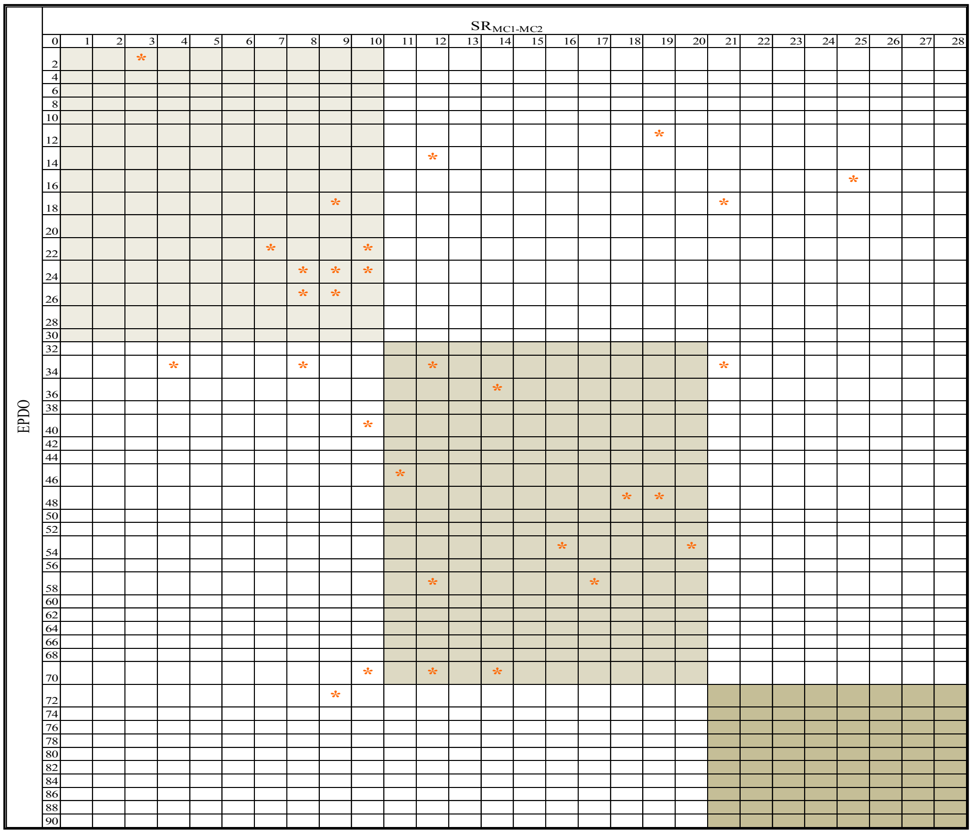

Fig 5. SR-EPDO grid for Curve/Curve combination

Table 6. Geometric design consistency evaluation criteria for successive elements

Evaluation	Tangent/Curve	Curve/Curve
Good	SR ≤ 15 km/h	SR ≤ 10 km/h
Fair	15 km/h < SR ≤ 30 km/h	10 km/h < SR ≤ 20 km/h
Poor	SR > 30 km/h	SR > 20 km/h

5. Application

This section illustrates application of the models developed and the criteria derived in this study to evaluate the geometry of a multiple horizontal curve. Table 7 shows the radii and curve lengths of the selected multiple horizontal curve. Operating speed models developed for All vehicle category at the midcurve locations were used to estimate the speed reduction experienced at the site. Speed Reduction from first curve to the second curve is 5.8 km/h which shows that consistency rating of the site is 'Good'.

Table 7. Consistency evaluation of a multiple horizontal curve

R_1(m)	CL_1(m)	R_2(m)	CL_1(m)	V_{85MC1}(km/h)	V_{85MC2}(km/h)	$SR_{MC1-MC2}$ (km/h)	Rating
150	120	80	50	54.0	48.2	5.8	Good

6. Conclusions

Evaluation of geometry for consistency in design is a novel approach for enhancing safety in rural highways. The study was done mainly to develop a geometric design consistency evaluation criterion for multiple horizontal curves for two-lane rural highways that is applicable to the Indian conditions. Operating speed based consistency measure was adopted in the study. To predict operating speed from alignment geometry, regression models were developed relating operating speed and geometric variables. Operating speed at tangent is found to be influenced by preceding tangent length. Operating speed at middle of first curve is influenced by radius and length of curve. Operating speed at the middle of second curve is influenced by radius of first and second curves. Deviation of operating speed from design speed is the consistency measure identified for evaluating a curve and speed reduction is the consistency measure identified for successive elements. Criteria were developed based on the Equivalent Property Damage Only crash values and consistency measure. Knowing the geometry of the alignment, it is then possible to evaluate the design of multiple horizontal curves of two-lane rural highway.

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