DOI:10.18869/modares.Ecopersia.5.1.1669 **2017, 5 (1): 1669-1682**

Determining Minimum Radius Length of Circle Horizontal Curves According to Pavement Damages

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Received: 31 August 2016/ Accepted: 8 January 2017 / Published Online: 20 March 2017

ABSTRACT Finding a minimum allowable radius length of a circle horizontal curve is essential to reduce earthwork cost or damage to the forest ecosystem, as well as make driving more comfortable. The present study is conducted i) to analyze different radius lengths of circle horizontal curves using an integrated approach consists of a Civil3D in concert with the field surveys, and ii) to propose a set of geometric design criteria which are more consistent with the existing condition of forest road network in Hyrcanian forest, north of Iran. Depth of the rutting (i.e., machine footprint) and soil mechanical properties are examined for a total of 36 existing horizontal curves with different radius lengths. Further, technical characteristics (i.e., stopping sight distance, horizontal sight line offset and turning speed) and a few parameters on pavement damage are included and incorporated into the research objective. No-statistical differences between radius lengths of the horizontal curve for classes of 10-15 and 16-20 m may associate with dissimilarity in the soil mechanical properties and in the dimension of the rut depth. These findings confirmed that it is therefore possible to shorten allowable radius length of a circle horizontal curve to at least 12 m under a longitudinal slope of 5% for forest road network in the north of Iran.

Keywords: *Civil3D, Horizontal curve, Hyrcanian forests, Road network, Soil mechanics*

1 INTRODUCTION

Horizontal curves are the most important geometric parts of the forest roads network, which are essentially designed based on valley and ridge features to make driving comfortable. Non consideration of a minimum-curve radius entails additional cost and excessive damage to the forest ecosystem (Heninger *et al.*, 2002; Stückelberger *et al.*, 2007). The fact that minimizing damage is a basic role to road planners to keep the ecosystem, sustainable, and maintain road system serviceability, thus, it is imperative to take advantageous of these benefits which could be achieved through better planning of the road system and well-adjusting of technical capabilities (e.g., road tangents or curves) that are aligned in spirit with the realistic conditions of the terrain. According to a few traditional forest road engineering textbooks (e.g., standards guide nos. 131 and 148) a minimum radius length of circle horizontal curve is suggested to 16 m for the secondary forest roads network in Iran (i.e., see Sarikhani and Majnonian 1999). Sometimes, one

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may find curves that have been constructed with a length below this value. Admittedly, such a curve provides a low stopping sight distance for safe driving, although they might be reasonable if pavement quality and safety requirements taken into consideration (Purohit *et al.*, 2011). Recently, this myopic focus has been increasingly criticized, because the omission of both terrain conditions and geometric design standards during planning practices (Ezzati *et al.,* 2016). Improper design of the road component such as horizontal curves can lead to excessive damages to forest ecosystem, both of the ecological and of the engineering aspects. To do so, it is therefore, required to consider and analyze these capabilities either when the project will launch or where it needs to be implemented on the ground (Parsakhoo *et al.*, 2010). It has been reported that curves with smaller length not only lead to increase costs of road maintenance and upgrading (Gendron *et al.,* 2016), but also caused creases design and/or traffic speeds and safety requirements (Session *et al.,* 2007).

Gravel is often brought to a road building location from either streams or quarries to protect the road surface, permit safe travels, increase transport productivity and minimize the adverse impact of road network to water quality and fish habit and wildlife habitat wildlife. A poor road surfaces including coarser gravel with organic matter, causes excessive damages to circle horizontal curves, especially, those of with smaller lengths (Miller *et al.,* 1998; Liu *et al.*, 2009). A useful criterion for determining the strength of subgrade material is California Bearing Ratio (CBR), which it indices of the thickness of the pavement material and swelling potential can be indexed (Kaakkurivaara *et al.,* 2015).Subgrade compaction will depend on the types of material used and the control of surface moisture contents during compaction. Coarse-grained soil composition of finer clay particles provides a slippery condition, especially when moist content of a soil is increased and its liquid limit reached to critical levels. Plastic-clay material exhibits shrink/swell behavior with moisture variability (Sharma *et al.*, 2008; FaridGiglo *et al.*, 2014), which may cause serious damages to pavement material (Azzam 2014). A rut usually defines as a wheel depression (i.e., depends on the amount of ground pressure) that formed over the road surface by trafficking vehicles, in when content of the soil moisture is in its high level. Ruts increase truck maintenance costs and decrease truck speed as well as reduce safety (Sessions 2007; Anderson *et al.,* 2009). Wheels scuff the road surface, especially where vehicle brakes prior to reaching the curve. This certainly leads to deeper ruts and washboards on the road surface (Jaarsma and Willems 2002). Horizontal curves are the most important geometric parts of forest roads network, which are essentially designed based on valley and ridge features to make driving comfortable. Neglecting of minimum-curve radius entails additional costs and excessive damages to the forest ecosystem (Heninger *et al.,* 2002; Stückelberger *et al.*, 2007). Minimizing damage is a basic role to road managers to keep ecosystem sustainable and maintain roads system serviceable. Therefore, benefits could be achievable through efficient planning of road network and well-adjusting of technical capabilities (i.e., road tangents, curves, etc.) that are consistent with the realistic conditions of the terrain. According to a few traditional textbooks on forest road engineering (e.g., standards guide nos. 131 and 148), 16 m is a minimum radius length suggested for a circle horizontal curve for secondary forest roads network in Iran (Sarikhani and Majnonian, 1999). Sometimes, one may find curves that are primarily constructed with a length below this value. Admittedly, such a curve provides a low stopping sight distance for safe driving, although they might be satisfactory if pavement quality and safety requirements are taken into consideration (Purohit *et al.,* 2011). This myopic focus has been increasingly criticized, because the omission of either terrain conditions or geometric design standards during planning practices (Ezzati *et al.*, 2016). Improper design of the road access network, especially, horizontal curves can lead to excessive damages to forest ecosystem, both ecologically and engineering aspects. Therefore, appropriate measure should be considered before launching a project (Parsakhoo *et al.*, 2010). It has been reported that curves with smaller length not only lead to increasing costs of road maintenance and upgrading (Gendron *et al.*, 2016), but also cause decreases in design and/or traffic speeds and safety requirements (Sessions *et al.*, 2007).

Gravel is often brought to a road building location from either streams or quarries to protect the road surfacing, safe passage, increase transport productivity, and minimize the adverse impact of roads network to water quality and wildlife habitat. Road surfacing with poor material, including coarser gravel with organic matter causes excessive damages to circle horizontal curves, especially those of with smaller lengths (Miller *et al.*, 1998; Liu *et al.*, 2009). Useful criteria for determining the strength of subgrade material is California Bearing Ratio (CBR), through which the thickness of the pavement material and swelling potential can be indexed (Kaakkurivaara *et al.*, 2015). Subgrade compaction will depend on types of material used and the control of moisture during compaction. Coarse-grained soils compose of finer clay particles provide a slippery condition, especially when moist content is increased. Plastic-clay material exhibits shrink/swell behaviour with moisture variability (Sharma *et al.*, 2008; Farid Giglo *et al.*, 2014), which may cause serious damages to pavement material (Azzam, 2014). A rut usually defines a wheel depression formed over the road surface by trafficking vehicles, especially when moisture content of soil is high. Ruts reduce the speed and safety of the truck, but increase its maintenance costs (Sessions, 2007; Anderson *et al.*, 2009). Wheels scuff the road surface especially where vehicle brakes prior to reach the curve. This certainly leads to deeper ruts and washboards on the road surface (Jaarsma and Willems, 2002). AutoCAD Civil 3D is a civil engineering design and documentation solution enables road designers to provide feasible solutions and enhance project performances in concert with other regulations which certainly much faster than traditional methods. The present study aimed at (i) presenting an integrated system; includesCivil3D together with field checking to quickly analyze the geometric design of circle horizontal curves and propose a set of geometric design criteria which are more consistent with the existing condition of forest road network in Hyrcanian forest, northern Iran and (ii) developing the relationships between geometric design standards and independent variables (e.g., liquid limit, plastic limit, dry density and CBR) for existing circle horizontal curves. Additionally, the methodology attempts to do a comparative analysis for existing circle horizontal curves with a set of technical criteria (e.g., stopping sight distance, horizontal sight line offset, turning speed and pavement damages). The resulting findings would be utilized as a practical tool for determination of the minimum allowable radius length of a circle horizontal curve using a set of geometric design standards that are being consistent with the real conditions of the road network in the Hyrcanian region in north of Iran.

2 MATERIALS AND METHODS

2.1 Study area

The study was conducted in a forest area of approximately 2,324 ha, located in southeast of the Sari province (between 36° $19^{'}$ $00^{''}$ N and 36° $21^{'}$ $20^{''}$ latitude and 53° $10^{'}50^{''}$ E and 53° $15^{'}55^{''}$longitude), north of Iran. The forest is managed by the company of wood and paper industries in the Mazandaran region. Elevation of the area ranges from 300 to 970 masl. The forest is a mixed stands with Hrnbeam (*Carpinus betulus* L.) Oiental Beech (*Fagus orientalis* L.), and Ionwood (*Parrotian persica* C.A. Mey) being the dominant speciesthat managed under unevenaged regime. Geological features of the area include marly, limestones and lime conglomerates. Average annual precipitation is 723 mm with most falls in winter (sometimes in combination with snow) and the minimum is in June, with mean annual temperatures of 17°C. Approximately 10% of the area situated in a rough topography condition (above 30%), while the rest has a gentle slope gradient (below 30%).

2.2 Methodology

2.2.1 Field survey

A total of 36 horizontal curves are fully investigated in the area in polar methods using a manual compass and a taped meter. Dimension of ruts on the road surfaces across each curve is measured carefully. Stopping sight distance (*S* in meter) is affected by both turning speed (*V* in km h^{-1}) and coefficient of friction (*F*) between tire and road surface, which is often set to 0.4 for gravel road network as the case in practice (Parsakhoo 2013). To compute turning speed, we established how long it takes for each vehicle to travel a given distance for 10 times. Stopping sight distance calculated as in Parsakhoo (2013) based on Eq.1. The parameter of *M* is the middle ordinate or the horizontal sight line offset whose defines as a distance between road inside edge and sight line, it calculated as Eq.2. Curve length is also determined as Eq.3. Eventually, the distance of beginning and end of curve from point of intersection is calculated as Eq4.

$$S = V + \frac{0.13V^2}{30F} \quad (1)$$

$$M = r(1-\cos\frac{\beta}{2}) - (\frac{W}{2}+1.5) \quad (2)$$

$$L = \frac{\beta\pi r}{180} \quad (3)$$

$$t = r\tan\frac{\beta}{2} \quad (4)$$

where *r* is the radius length of a curve (m), *W* is the average width of travel way (m), β is the central angle of the curve (degree), *L* is the length of arc (m), *t* is the distances from an intersection point (*IP*) to a beginning (*BC*) and an end (*EC*) of a curve (m), and 1.5 is the length of shoulder and ditch (m) (Figure 1). The curves platting are carried out in Civil3D software, and statistical analyses are conducted into SPSS software version 14.

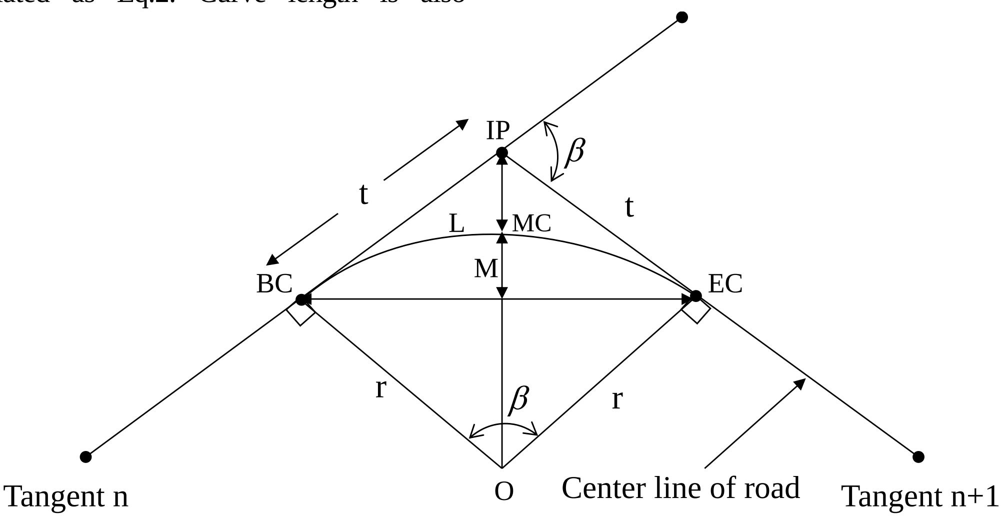

Figure 1 Geometry of a circular horizontal curve

2.2.2 Atterberg limits

Liquid Limit (LL) of soil sample determined as Eq.5 (Atterberg 1911):

$$LL = Wn_N \times \left[\frac{N}{25}\right]^{0.121} \tag{5}$$

where N is the number of drops of the cup required to close the groove, Wn is the soil moisture content (%) in which groove is closed. The soil moisture content is measured at which soil changes from liquid state to plastic state (i.e., at which two sides of a groove come close together for a distance of 12.7 mm under the impact of 25 numbers of blows. The plasticity index (*PI*) of a soil is the range of water content over. It defines as the numerical difference between the liquid limit and plastic limit (Atterberg 1911) that calculated as Eq.6.

$$PI = LL - PL \tag{6}$$

2.2.3 California Bearing Ratio (CBR)

The CBR value of a soil is associated with the strength of a soil (Yetimoglu *et al.,* 2005) that calculated as Eq. 7.

$$Y_d = \frac{Y_t}{1+Wn} \tag{7}$$

where Y_d equivalents to dry unit weight of the soil (g cm^{-3}), Y_t is the total unit weight (g cm^{-3}) and Wn is the soil moisture content (%).

2.2.4 Computer design

Horizontal and vertical alignments are generated in the Civil3D environment by plotting the location of both tangent lengths and points of intersection for a road alignment. Through the process, a circle horizontal curve is used to provide a transition between two tangents and generally can be designed either automatically or manually. To address high speed travelled, a spiral transition and a super elevation further adjusted to each curve. Numeric parameters therefore tuned for each alignment curve and spiral transitions same as with those are already recommended (e.g., see alignment entity tables in Sarikhani and Majnonian 1999). The program is much friendly, it enables a user to insert or quickly modify parameters before or after platting a circle horizontal curve (Lugo and Gucinski 2000).

Collected information is statistically analyzed using a general linear model (GLM) procedure in SAS platform. Student-Newman-Keuls multiple comparison tests is utilized to compare mean values at the 5% level; numerical diagrams were also generated in an Excel package under Microsoft license.

3 RESULTS AND DISCUSSION

It is possible to reduce the overall cost of operations through efficient planning of road network and design of circle horizontal curves (Stückelberger *et al.,* 2007; Ghajar *et al.* 2013). However, safety requirements must be taken into consideration to possibly reduce both economic and environmental costs. In this study, the radius length of a curve is classified into five categories i.e., 10-15 m (A), 16-20 m (B), 21-50 m (C), 51-100 m (D), and 101-200 m (E). Every curve analyzed from technical geometric criteria as they are listed in Table 1. The results indicated that almost 86% of the curves had radius lengths of above 15 m.

The ANOVA test indicated that turning speed significantly influenced stopping sight distances, rut area and depth of rutting for all studied curves (Table 2).

Table 1 Technical geometric criteria of study circle horizontal curves. *t* = tangent length; *w* = average width of travel way; *β* = central angle of curve; *L* = length of arc; *V* = turning speed; *S* =stopping sight distance; *M* = middle ordinate or horizontal sight line offset

Radius class	Radius length of a curve (m)	Geometric criteria								
		t (m)	*W* (m)	*β* (degree)	*L* (m)	*V* (km h^{-1})	*S* (m)	*M* (m)	Rut depth (cm)	Rut dimension ($m^2 100m^{-2}$)
B	20.00	23.00	10.30	98.10	34.00	25.00	31.80	4.80	4.80	2.00
C	33.00	14.00	5.50	46.80	27.00	30.00	39.80	0.00	4.30	1.60
D	83.00	16.50	5.50	22.50	32.50	40.00	57.30	0.00	3.40	1.60
C	28.50	12.30	5.50	46.80	23.00	30.00	39.80	0.00	4.90	1.80
C	29.00	12.00	5.50	44.10	22.00	30.00	39.80	0.00	4.70	1.70
D	91.00	21.00	5.50	26.10	41.50	40.00	57.30	0.00	3.40	0.80
D	70.00	20.00	5.50	31.50	39.00	40.00	57.30	0.00	3.60	1.50
B	15.00	15.00	6.60	90.90	24.00	20.00	24.30	1.10	7.00	2.60
C	40.00	16.00	5.50	44.10	31.00	35.00	48.30	0.00	4.00	1.40
C	28.50	12.00	5.50	45.90	23.00	30.00	39.80	0.00	5.00	1.60
D	72.50	23.00	5.90	35.10	44.50	40.00	57.30	0.40	3.60	1.10
C	32.00	16.00	5.80	53.10	30.00	30.00	39.80	0.30	5.10	1.60
C	28.50	10.00	5.50	39.60	20.00	30.00	39.80	0.00	5.20	1.70
D	52.00	12.90	5.50	27.90	25.00	35.00	48.30	0.00	4.30	1.30
C	35.50	10.00	5.50	30.60	19.00	30.00	39.80	0.00	4.60	1.40
B	17.00	13.00	5.80	74.70	22.00	20.00	24.30	0.30	5.20	2.50
B	15.00	12.00	5.50	76.50	20.00	20.0	24.30	0.00	7.10	2.80
C	42.00	13.00	5.50	35.10	26.00	35.0	48.30	0.00	4.40	1.90
D	84.00	23.00	5.60	30.60	45.00	40.0	57.30	0.10	3.50	1.40
C	45.00	13.00	5.50	32.40	25.00	35.0	48.30	0.00	3.70	1.70
C	27.00	14.00	5.50	54.00	25.00	30.0	39.80	0.00	5.50	1.90
E	161.00	19.00	5.50	13.50	38.00	40.0	57.30	0.00	2.50	0.80
C	30.00	10.00	5.50	37.80	20.00	30.0	39.80	0.00	5.20	2.00
C	44.00	14.00	5.50	36.00	28.00	35.0	48.30	0.00	4.70	2.00
B	20.00	12.00	5.50	60.30	21.00	25.0	31.80	0.00	6.10	2.00
B	17.50	14.00	6.10	78.30	23.00	20.0	24.30	0.60	5.30	2.40
B	20.00	22.00	8.90	95.40	33.00	25.0	31.80	3.40	5.60	2.00
D	86.00	13.00	5.50	17.10	26.00	40.0	57.30	0.00	3.30	1.90
B	17.00	13.00	6.00	76.50	23.00	20.0	24.30	0.50	5.10	2.30
E	110.00	14.00	5.50	15.30	28.00	40.0	57.30	0.00	2.40	1.20
B	15.00	18.00	7.80	101.70	27.00	20.0	24.30	2.30	7.20	2.70
E	185.00	17.00	5.50	10.80	35.00	40.0	57.30	0.00	2.20	0.90
C	29.00	10.00	5.50	39.60	20.00	30.0	39.80	0.00	4.10	2.10
D	57.40	23.00	6.30	44.10	44.00	35.0	48.30	0.80	3.60	1.40
A	13.00	13.50	6.30	92.00	20.90	20.0	24.30	0.80	5.90	2.50
A	12.00	11.60	5.60	88.00	18.40	20.0	24.30	0.10	5.40	2.20
Average	**48.10**	**14.90**	**5.93**	**48.40**	**27.70**	**30.80**	**41.70**	**0.30**	**4.60**	**1.70**

A stopping sight distance might be restricted by overgrowing trees on the right of way and exposing the steep cut slope, so it highly recommended frequently grabbing invasive tree or clearing brush on the right of way at least twice every year and laying back the ridge slope failure to improve sight distance and make driving more comfortable (Sessions 2007; Nguyen *et al.*, 2008).

A turning speed of 40 km h^{-1} would thus suggest lengths of the tangent should not be too long (Crossley *et al.*, 2001). Interestingly, there are statistical differences among curves with different radius lengths in terms of the horizontal sight line offset (*P*=0.0086). Despite no variability of turning speed among curves with different radius lengths of 10-15 m (A) and 16-20 m (B), turning speed is increased significantly for the curves with higher lengths (i.e., above 21 m; see Figure 2).

Akay *et al.* (2008) reported that depth of rutting is affected by geometric design factors include the radius length of the curve, turning speed and dynamic weight of the vehicle. The stopping sight distance is calculated 25 m in radius classes of A and B, which is significantly lower than those values observed for other classes (see Figure3).

Table 2 The ANOVA of the different variables of turning speed and pavement damage for circle horizontal curves.*V* = turning speed, *S* = stopping sight distance, *M* = horizontal sight line offset

Source of variance	*df*	Sum of square	Mean square	*F* values	*P* values
V (km h^{-1})	4	1,748.71	437.17	85.27	< 0.0001
S (m)	4	4,761.64	1,190.41	83.79	< 0.0001
M (m)	4	12.72	3.18	4.12	0.0086
Rut depth (cm)	4	41.44	10.36	27.86	< 0.0001
Rut dimension (m^2ar)	4	7.06	1.76	23.99	< 0.0001

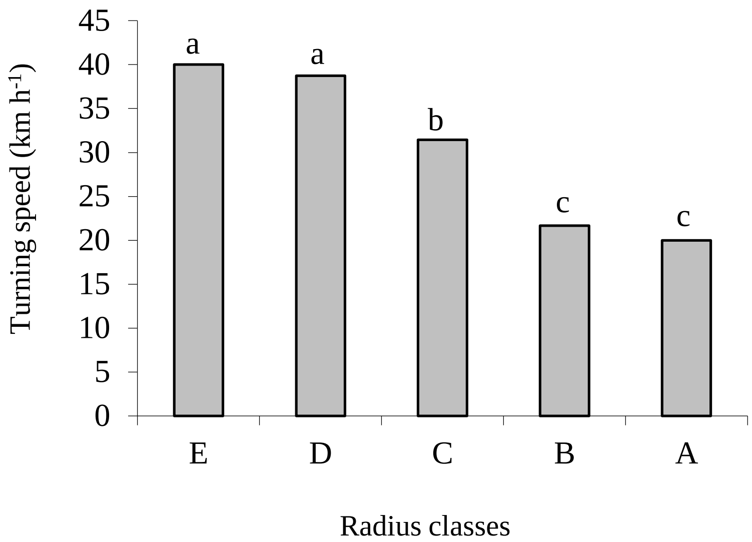

Figure 2 Effect of turning speed on different radius lengths of curve

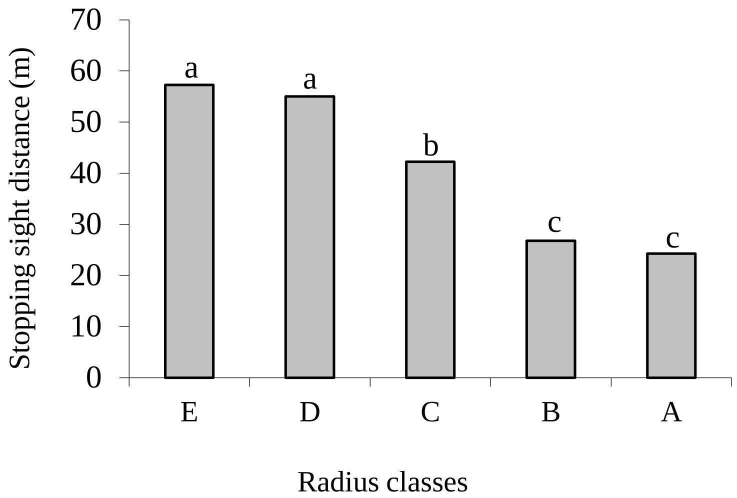

Figure 3 Effect of stopping sight distance on different curve radius classes

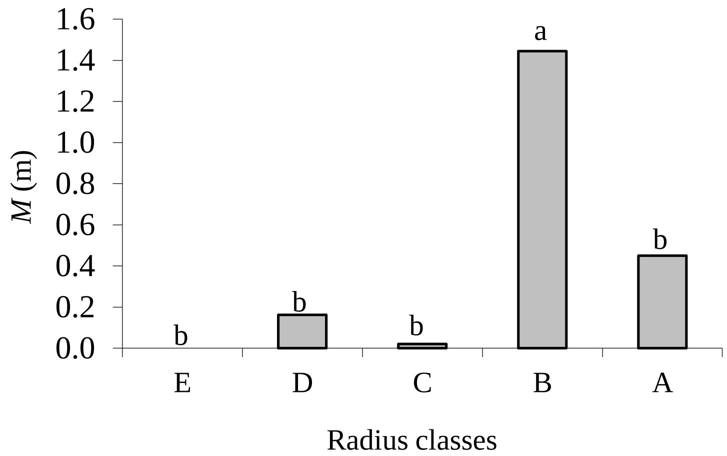

Figure 4 Effect of horizontal sightline offset on different radius lengths of curve

It can be concluded that the *M* might be a useful parameter for determining amount of required earthwork on the crest of the curve to provide visibility of the area. Our findings confirmed that a higher value of *M* (i.e., a horizontal sight line offset) observed in which a curve has a small radius length (i.e., below 20 m; Figure 4).

Anderson *et al.* (2009) indicated that rut width, rut index and depth of rutting increased with decreasing radius length. In our case study, the rut index calculated through combining rut depth and width of rutting. Rut depth decreased with increasing length of the radius. The greatest rut depth of 6 and 7 cm are measured on curves with smaller lengths of 10-15 m (A) and 16-20 m (B), respectively (Figure 5). It anticipate a deeper rut (i.e., more than 15 cm in depth) will result in serious damages to base layer and subgrade layer of a road, so where depth of rut is increased from 5 cm to 12 cm, reshaping and smoothing requirements would immediately require on the surface of road.

Neglecting such maintenance requirements incur uncomfortable driving, loosen surface material quickly and further increase the cost of the maintenance and upgrading (Way *et al.,* 2005; Sessions *et al*. 2007).

The results well consistent with Talebi *et al.* (2015) who reported a higher depth of rut is seen on the road surface, particularly where the radius length of a curve is too small. Figure 6 shows that the rut area is measured significantly greater for the radius classes of A and B in contrast with later classes, albeit, the differences are not statistically significant in contrast with earlier classes. Indeed, either area or the number of rutting increased with decreasing radius length. Increase number of ruts might be directly associated with bed laxity or low resistant surfacing (Talebi *et al.,* 2015), which imposed by exerting load on the ground that exceed road pavement capacity.

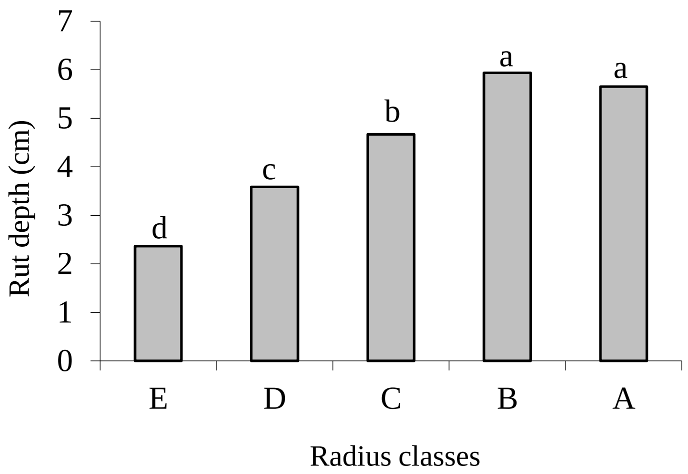

Figure 5 Effect of rut depth on different radius lengths of curve

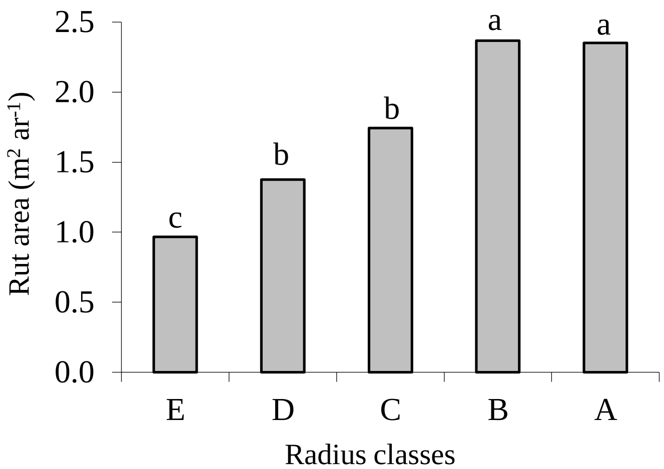

Figure 6 Effect of rut area on pavement of on different radius lengths of curve

In the current study, pavement materials are composed of 46% gravel, 32% sand and 22% silt and clay. Figure 7 confirms that the liquid limit and plastic index are decreased to 4% and 3%, respectively, by decreasing radius length. In general, soils with higher of plasticity limit and of liquid limit are not suitable, because of bearing compressibility and water permeability, which allow surface flow to penetrate into the sub-base and destroy the road body as quickly as possible (Ryan *et al.*, 2004). A higher pressure (e.g., both horizontal and vertical) and shear stress exerted by the vehicle wheels would be expected, especially, in which the curve has a small radius length (Kozlowski, 2000; Ezzati *et al.*, 2012; Solgi *et al.*, 2016). Machine induces soil compaction owing to the exerted normal pressure and vibration, which it may imply reduction of the content of soil moisture (Ampoorter *et al.*, 2007; Ezzati *et al.*, 2012) and, therefore, instantaneous reduction of the liquid limit and plastic limit. In addition, increases in traffic intensity can directly affect soil bearing capacity and loose of pavement material (Miller *et al.*, 1998). The CBR values decreased from 89% (i.e., radius class A; 10-15 m) to 71% (i.e., radius class E; 101-200 m) with increasing radius length (Figure 8). Evidence of the linear relationship between CBR and soil density or soil moisture content is also found by Crossley *et al.* (2001), for a variety of soils.

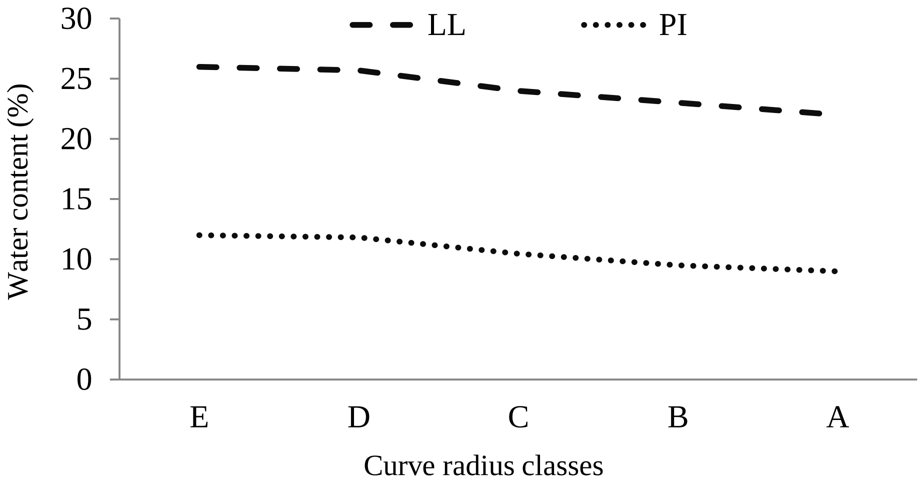

Figure 7 Atterberg test limits, including plastic index and liquid limit for different radius lengths of curve

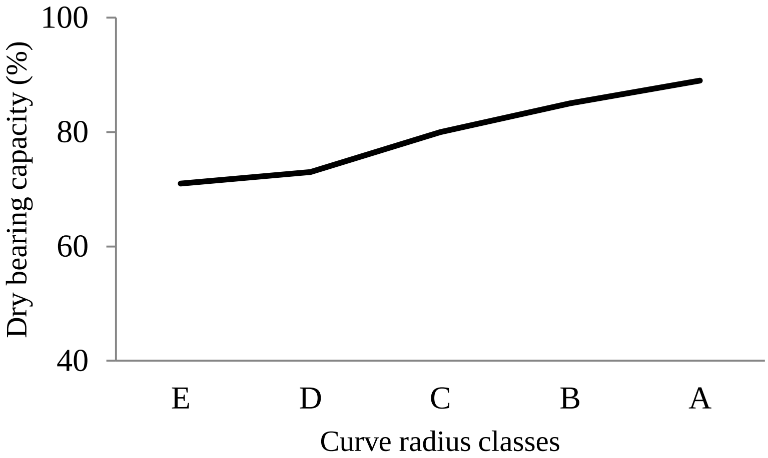

Figure 8 Variations of California bearing ratio (CBR) test by increasing length of the radius of curve

4 CONCLUSIONS

Determining a minimum allowable radius length of a horizontal curve is important as an effective geometric design factor for forest road network under a particular set of conditions. Non-significant differences between curves with small radius length of 10-15 m and 16-20 m are strongly related to the level of soil mechanical properties and depth of rutting, which confirmed the fact that it would be possible to consider a smaller radius length for circle horizontal curve on secondary forest road network. Very few of the ruts are observed where either the radius length of a curve is larger or a road surface is more stable (i.e., high CBR).

It is assumed that choosing an appropriate road gradient and a feasible radius length of circle horizontal curves is imperative, it might lead to minimize road maintenance and upgrading cost, in particular, where the slope gradient is less than 5% and minimum radius length of a curve is set to above 12 m, but that is left to be seen and requires more field research. In the current case study, turning speed decreased to 21 km h^{-1}. Future work with AutoCAD civil3D involves the development of better vision of a road segment need to be included into the objective, especially for in which a realistic, large-scale plan is of concern.

5 ACKNOWLEDGEMENTS

The research is supported by Gorgan University of agricultural sciences and natural resources. We would like to acknowledge experts and local harvesting teams for their kindly assistances in logistics and data collection.

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تعیین حداقل شعاع قوس بر اساس میزان خسارات به بستر روسازی در شبکه جاده‌های جنگلی

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تاریخ دریافت: ۱۰ شهریور ۱۳۹۵/ تاریخ پذیرش: ۱۹ دی ۱۳۹۵ / تاریخ چاپ: ۳۰ اسفند ۱۳۹۵

چکیده حداقل شعاع مجاز قوس‌های افقی برای شبکه جاده‌های جنگلی ضروری بوده، که منجر به کاهش هزینه عملیات خاکی و خسارات به اکوسیستم جنگل شده و عبور ایمنی را فراهم می‌سازد. مطالعه حاضر به ارزیابی قوس‌های افقی با طول شعاع متغیر و پیشنهاد معیارهای فنی مطابق با شرایط جنگل‌های خزری در شمال ایران، با استفاده از یک رویکرد ترکیبی؛ استفاده از روش کامپیوتری Civil3D به همراه بازدید میدانی پرداخته است. ابعاد شیار (جای چرخ ماشین) و خصوصیات مکانیکی بستر جاده‌سازی برای ۳۶ قوس افقی با شعاع‌های متفاوت اندازه‌گیری شد. همچنین، خصوصیات فنی (فاصله دید توقف، فاصله اطمینان دید و سرعت قوس) و خسارات وارده به بستر روسازی جاده، نیز اندازه‌گیری و ثبت شد. تجزیه و تحلیل داده‌ها نشان داد که ارتباط معنی‌دار ضعیفی بین خصوصیات مکانیکی و اندازه شیار با قوس‌های با شعاع ۱۵-۱۰ و ۲۰-۱۶ متر و ۲۰-۱۶ متر وجود دارد. این نکته بیانگر این واقعیت است که شعاع مجاز قوس افقی می‌تواند کمتر از استانداردهای فعلی باشد. بنابراین، تحقیق حاضر نشان داد که شیب طولی مجاز ۵ درصد و شعاع قوس افقی ۱۲ متر در جنگل‌های شمال ایران مناسب و امکان‌پذیر می‌باشد.

کلمات کلیدی: Civil3D، جنگل‌های هیرکانی، شبکه جاده‌های جنگلی، قوس افقی، مکانیک خاک