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Evaluation of Horizontal Curve Superelevation Using Road Surface Profiler (RSP)

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Abstract: Riding comfortably and safely through horizontal curves in roadways should be provided by superelevation. Asphalt overlaying during the maintenance period could change superelevation (reduce or reverse it); thus, assessing a road's cross slope along curves is of great importance. In this research, the Road Surface Profiler (RSP) device was used to measure superelevation at a curve in a newly constructed Shahroud-Miami roadway. It was chosen because of the availability of curve parameters such as start/end points, radius, superelevation, and design velocity. A good agreement was found between superelevation measured by RSP and that of the curve design. Also, it was found that rate of turn (RT) profile is a suitable tool to determine the start/end points of curves, which is a basic step in assessing curve superelevation. Three horizontal curves of Andimeshk ring were then tested by the RSP device and analyzed based on findings from the curve in Shahroud-Miami. Results show that all three curves have a superelevation shortage of approximately 3%. In these cases, the temporary solution is to install a new "Posted-Speed" sign based on existing curve superelevation.

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***Key words**: Cross slope; Curve radius; Horizontal curve; Rate of turn (RT); Road surface profiler (RSP).*

Introduction

Providing comfort and safety are important parameters in horizontal curves. The balance of the vehicle while passing through a curve is secured by superelevation [1]. Superelevation is directly dependent upon how the pavement is constructed. Lack of attention to road construction or inappropriate implementation of asphalt overlay during the maintenance period results in reduced comfort and safety of the curves.

There are several methods for collecting cross slope data, but surveying techniques to collect data, accuracy, cost, speed of collection, and safety considerations are varied. Conventional survey techniques use manual methods to collect coordinate points. Surveyors use levels, rods, and electronic devices for site measurement. The point and elevation data are extremely accurate; however, the time required for data collection coupled with reduced safety and restricted traffic operations makes this approach infeasible for large-scale project databases. Survey techniques in concert with hand-held GPS equipment can provide accurate results, but have disadvantages similar to those of the manual method. Locating survey equipment in a static vehicle permits data collection with improved safety. The vehicle is typically positioned on the shoulder of roadway, and with the aid of an electronic data collector, disto-meter, notebook computer, and GPS unit, accurate results can be obtained for the pavement cross section. However, the required equipment is costly, and the vehicle cannot be in motion during data collection [2].

The use of technology developed for the defense industry incorporates a gyroscope and accelerometer to provide heading, pitch, and roll angle. The PosNav system developed by the Michigan Department of Transportation in 1992 could collect data accurately and in a short period due to kinematic data collection [2]. The other survey system, which used a GPS unit, camera cluster, and gyroscope, was VIASAT mobile highway survey system [3]. These inertial system provide various levels of accuracy; however, the equipment expense is generally identified as the biggest disadvantage of these alternative methods. Georgia Tech developed a new method, which uses a specialized GPS unit with multiple antennas connected to a multichannel GPS receiver and a notebook computer. The method is called GPS-based Attitude, in which vehicle attitude is computed and post processed to determine grade and cross slope data [3]. A 2009 study used GPS to collect data to compute radius and angle data. The researchers used a digital ball-bank indicator to measure superelevation and compiled curve data using Texas Roadway Analysis and Measurement Software (TRAMS) [5]. A GPS-based method that includes GIS applications was used to collect and analyze horizontal curve geometry data. The researchers collected field data at 0.1-second intervals using differential GPS. They showed that GPS could produce longitudinal pavement profiles quickly and cheaply with acceptable accuracy [6].

In addition, the effect of geometric parameters on road safety has been considered in many research projects. Bonneson et al. developed a relationship between injury and fatal crash frequency and curve design [7]. Pitale et al. suggested a similar relationship between crash rate and curve radius. However, the crash rates for 1,500 feet radius curves were twice as high as those with 2,000 feet [8]. Choi et al. demonstrated how the superelevation and side friction factors over a range of curve radiuses affect smart highway design [9]. Haung et al. optimized modeling of superelevation rates based on operation speed by investigating accidents from 2001 to

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2007 in China [10]. This project focused on superelevation (cross slope in horizontal curves of road). Superelevation is one of the primary factors affecting road safety. The reviewed methods are not appropriate due to high time consumption, high traffic disruptions, and the inability to provide a large database. In addition, GPS-based method disadvantages inclue their inability to be used everywhere—for example, curves in tunnels or in urban areas—due to limitation in receiving signals. That is why a more rapid and accurate method is required to survey road geometry. This research is based on field data gathering using a device called the Road Surface Profiler (RSP).

Superelevation

In road horizontal curves, superelevation, together with the centrifugal force, helps provide balance between wheel-pavement side friction force and the vehicle weight component [1, 11]. Eq. (1) is established between superelevation and factors affecting the balance of the vehicle in horizontal curves [1,4]:

$$e + f = \frac{V^2}{127.2R} \tag{1}$$

In which:
e: the amount of superelevation in terms of percentage
f: side friction coefficient depends on vehicle speed
R: radius of curve in terms of meter, and
V: design speed in terms of kilometer per hour.

The side friction coefficient of the pavement depends on factors such as tire condition, design speed, surface humidity and pavement type. The maximum amount of the superelevation is subject to the following factors:

- The climatic conditions of the area (frequency and amount of snow and ice)
- Road type (mountainous, hilly or flat)
- Number of heavy vehicles
- Design limitations in terms of providing adequate space to execute superelevation and conditions for surface water drainage.

According to the Iran Highway Asphalt Paving Code No. 234, during road construction, superelevation should be implemented in the subgrade and controlled after executing each pavement layer [12]. The maximum amount of superelevation for primary/main roads and freeway/highway without snowfall and frost is 12 and 10 percent respectively. In regions with more than 1,000 meters elevation from sea level, superelevation is limited to 8% to avoid slow-moving vehicles slipping downhill toward the inside of the curve. In order to ensure safety and avoid sudden changes in the way, superelevation and radius of curve vary gradually using two transition curves before and after the horizontal curve [1, 4].

RSP Introduction

RSP is used to determine the roughness and geometric properties of road and airport pavements. The device is capable of collecting pavement surface profiles up to 110 km/h without any traffic disruption, hence, it is considered as one of the fast non-destructive equipment types for pavement evaluation. RSP enjoys seven lasers and two accelerometers in a box located in front of the vehicle, which are used to measure pavement profile along the wheel path. Also, geometric properties of the road including longitudinal slope, transverse slope (cross slope), and rate of turn (RT) are measured using Inertial Motion Sensors (IMS). The RSP is equipped with an accurate Distance Measuring Instrument system (DMI), Global Positioning System (GPS), and a camera by which images of the road can be stored. Fig. 1 illustrates the RSP test system.

In Table 1, device outputs along with the hardware components involved in measurement of each mentioned parameters are presented. In this study, IMS data including velocity, cross slope, and rate of turn (RT) are used to evaluate superelevation in horizontal curves [13].

The IMS unit of RSP is used to collect and derive geometric data of pavement including grade (pitch), cross slope (roll), and turn rate (yaw rate). These parameters are schematically illustrated in Fig. 2. The cross slope (roll) of the transducer beam together with cross slope of laser profile are used for real-time calculation of the cross slope of the pavement. The IMS type used in the RSP device is Watson AHRS-E304. It is a 3-axis solid-state gyroscope with a 3-axis accelerometer and a magnetometer to provide earth references. The IMS communicates with the RSP via an RS-232 serial port [13].

Rate of Turn

Rate of turn (RT) or angle velocity is the rate of the vehicle rotation in curves and can be measured by IMS in terms of degree per second. Positive values of RT refer to right turn curves and negative values state the left turn curves. RT can be measured in 5 or 10-meter intervals along the road and can be presented simultaneously during data gathering [13]. Eq. (2) defines calculation of circular curve radius:

$$R = \frac{180 \times V}{3.6 \times \pi \times \omega} \tag{2}$$

Where V is vehicle speed in term of kilometer per hour and is measured accurately by RSP device; ω is the RT in terms of degree per second. Since, the RT value equals approximately zero in straight ways, the start and the end points of curve can be easily determined. The curve cross slope is then obtained by coinciding the start and the end position from RT profile to road cross slope profile. Fig. 3 shows a RT profile along the road, and the curve start and end points as well as type of curve direction are specified schematically. This procedure is more applicable to roads that were constructed years ago, due to hard determination of curve start and end locations.

Pavement Cross Slope

RSP measures the road cross profile by means of lasers and IMS. The slope of the transducer beam and linear regression of laser points are measured to calculate pavement cross slope, and this is called superelevation in the areas of horizontal curves [13]. Fig. 4 illustrates the procedure of cross slope determination. The difference between slope of linear regression line of lasers and slope of transducer beam is equal to pavement cross slope or

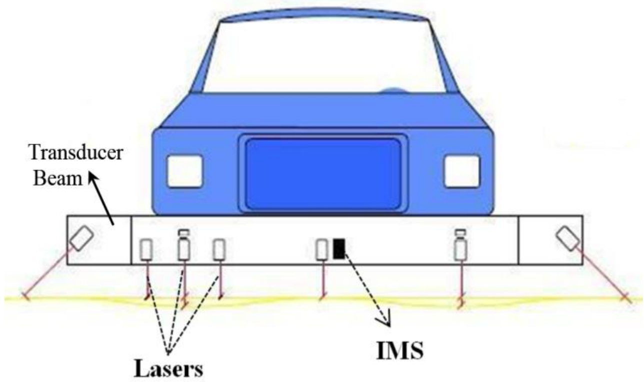

Fig. 1. Schematic View of 7-Lasers RSP Test System.

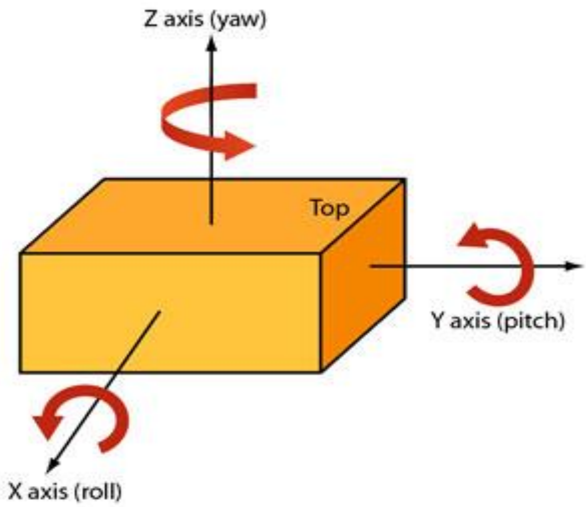

Fig. 2. Initial Motion Sensors Performance [13].

Table 1. Output and Different Parts of the RSP Device [13].

Parameter	Hardware
International Roughness Index (IRI)	Lasers and Accelerometers
Ride Number (RN)	Lasers and Accelerometers
Rutting	Lasers
Macro Texture	High Frequency Lasers
Radius of Curve	IMS(Inertial Motion Sensor)
Grade	IMS(Inertial Motion Sensor)
Cross Slope	IMS and Lasers
Positioning	GPS - DMI
Image Storing at User Specified Interval	Camera

superelevation.

Research Methodology

This paper focuses on introducing an innovative way to measure existing pavement geometric parameters, especially cross slope. The first question in evaluating superelevation is to determine the start and the end points of the curves. Radius and cross slope are then calculated in the areas of curve. Therefore, this research was conducted in two phases. In phase 1, a horizontal curve in Shahroud-Miami roadway in the Semnan province (newly constructed road) was selected. It was chosen because of the availability of the curve parameters such as start/end points, radius, cross slope, and design velocity. These parameters were taken from the Semnan Road and Transportation Agency (SRTA) as shown in Table 2. The agency claimed that the existing curve parameters resulted from using a surveying camera. In this table, the shaded part belongs to circular curve. In the first phase, measuring parameters using RSP were compared with designed values. In phase four, points presented in Table 2 were marked on the road surface for best comparison between data resulted from RSP and designed ones. RSP was then used to measure the profile of RT and cross slope at every 5-meter interval. When the RSP met marked points during data collection, the operator pressed a suitable key on the laptop to record the location of points in the software. This phase ensured the accuracy of the measuring data and proper performance of RSP in evaluating superelevation. In phase two, findings from phase one were used to evaluate three curves of Andimeshk ring. Khuzestan Road and Transportation Agency (KRTA) specified these curves to evaluate due to the availability of more statistics on traffic accidents.

Data Analysis

The transition curve is used where a straight section changes into a curve. It is designed to prevent sudden changes in lateral (or centripetal) acceleration. It also helps to change radius of curvature gradually and provides adequate length to apply superelevation [11].

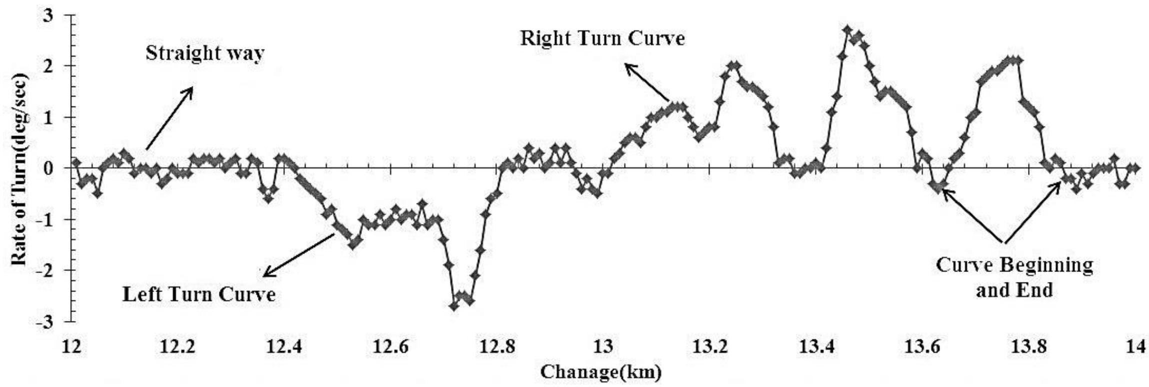

Fig. 3. RT Profile.

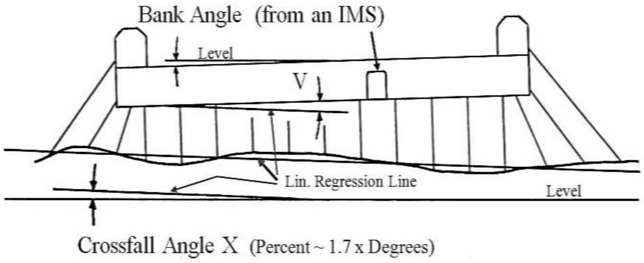

Fig. 4. Procedure of How Cross Slope is Calculated from RSP Device Data.

Table 2. The Geometric Design Parameters of Shahroud-Miami Horizontal Curve Taken from SRTA.

Chainage (m)	Point	Super Elevation (%)	Length (m)	Radius (m)
0	Start of Transition Curve	1.5		
25		1.5	75	---
50		2		
75	End of Transition Curve Start of Circular Curve			
		3.5	350	1500
425	Start of Transition Curve End of Circular Curve			
450		3.5		
475		3.4	75	---
500	End of Transition Curve	1.6		

Fig. 5 shows the RT values measured by the RSP in the selected curve of Shahroud-Miami road. The start and the end of the horizontal curve are indicated in Fig. 5. The first part of the graph indicates the transition curve, in which RT of straight section increases to a circular curve gradually. In addition, the final part shows the transition curve that changes RT of circular curve to a straight section. RT is a suitable parameter to specify the start and the end points of curves. RT together with RSP velocity are used to calculated curve radius based on Eq. (2). Speed fluctuation of the RSP affects the RT significantly; as the device speed increases in the horizontal curve, the RT will be enhanced as well. To evaluate the curves, their locations are determined by RT index. The radius is then calculated by means of harmonic mean concept. Harmonic mean will result in an accurate answer if averaging is being done on ratio of two parameters (RT and RSP velocity). Eq. (3) demonstrates the mathematical concept of harmonic mean:

$$m = \frac{n}{\sum_{i=1}^{n} \frac{1}{x_i}} \tag{3}$$

in which, m = harmonic Mean; n = number of data; x = values of data

The radius and curvature (inversed radius) through the circular curve were calculated at each point, which is shown in Table 3. The radius is then resulting from inversing the mean curvature value in curve areas.

The comparison between the calculated radius (1,515 m) and design radius (1,500 m) shows the accuracy of the RSP device in measuring RT and calculating curve radius. Of course, in this roadway, curve radius has already been specified by SRTA. For old roads that were constructed many years ago and have undergone several maintenance periods, curve radius is not clear. This issue is due to difficulties in determining the start and end points of the curves. One of the best solutions for this matter is to use RT profile measured by RSP device. The RSP device measures curve cross slope at each point of the curve. Table 4 shows the amount of cross slope measured by RSP and designed ones at every 25-meter interval.

In addition to Table 4, Fig. 6 also illustrates a comparison of superelevation resulting from RSP with designed values. It shows a similar trend on both data sets. The superelevation graph in the figure can be divided into 3 parts including initial transition curve, circular curve, and final transition curve. Changes in superelevation resulted from RSP are more than designed values. RSP measures and records the cross slope continuously at each 5-meter by moving on the road surface. Designed superelevation in circular curves is constant and equal to 3.5%. At the start and end of the circular curve, RSP shows the same superelevation in comparison with SRTA. However, in the circular curve, it is identified that the RSP device measures the superelevation and its changes more accurately. The RSP operator should drive vehicle exactly on the center of lane to gather data properly; otherwise, errors will associate with the RT measurements. One of the main advantages of RSP is to measure cross slope while it's moving along the curve. So RSP is capable of best simulating vehicle attitude on the road and can measure geometric parameter every 1 m. In Shahroud-Miami, since the start

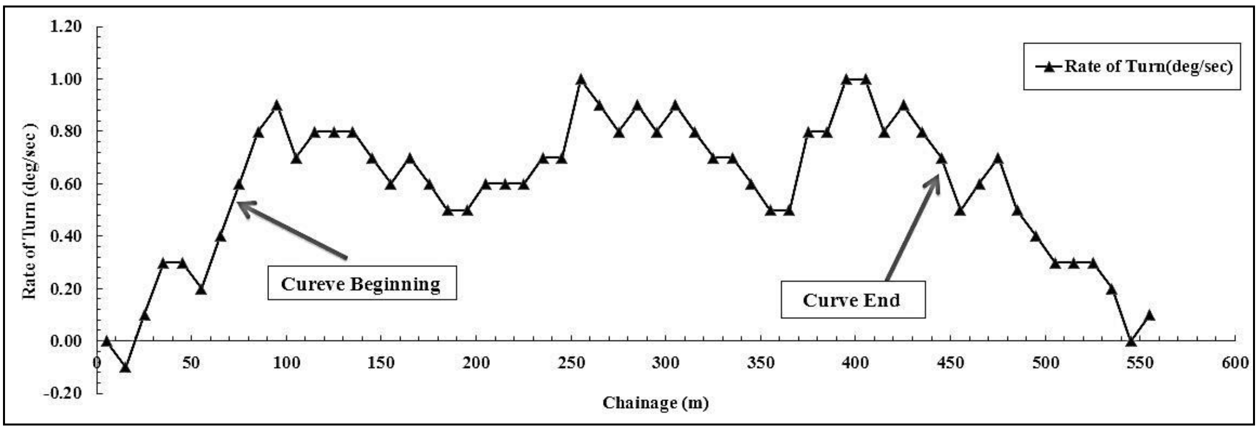

Fig. 5. The RT profile in selected curve of Shahroud- Miami road.

Table 3. Calculating Curve Radius in Shahroud-Miami road by RT.

Chainage (m)	RT(deg/sec)	**Speed**(km/h)	Radius(m)	Curvature (1/m)	Curvature Harmonic Mean (1/m)	Calculated Radius (m)
75	0.6	61.7	1237	0.000808	0.00066	1515
100	0.8	63.3	1357	0.000737		
125	0.8	64.7	1295	0.000772		
150	0.7	65.5	1385	0.000722		
175	0.6	66.4	2119	0.000472		
200	0.6	67	1783	0.000561		
225	0.6	67.6	1541	0.000649		
250	0.9	68.1	1143	0.000875		
275	0.8	68.4	1361	0.000735		
300	0.9	68.4	1449	0.000691		
325	0.7	68.2	1805	0.000554		
350	0.6	68.1	1661	0.000602		
375	0.8	67.8	2558	0.000391		
400	1	67.5	1259	0.000794		
425	0.9	67.2	1522	0.000657		
450	0.6	66.9	1773	0.000564		

Table 4. Designed Superelevation and RSP Measurement.

Chainage (m)	Superelevation (RSP) (%)	Superelevation (Design) (%)	Chainage (m)	Superelevation (RSP)(%)	Superelevation (Design) (%)
0	1.5	1.5	275	4.3	3.5
25	1.6	1.5	300	4.2	3.5
50	2.4	2	325	4.4	3.5
75[a]	3.1	3.5	350	4.5	3.5
100	3.7	3.5	375	3.8	3.5
125	3.8	3.5	400	4.1	3.5
150	3.5	3.5	425[b]	4	3.5
175	3.4	3.5	450	3.6	3.5
200	3.8	3.5	475	2.6	3.4
225	4.2	3.5	500	2.4	1.6
250	4	3.5	525	2	1.5

[a]Start of circular curve [b]End of circular curve

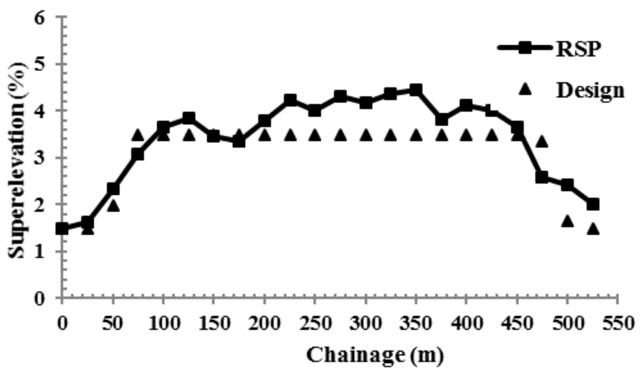

Fig. 6. Measured Superelevation by RSP Versus Designed Values in Shahroud–Miami Road.

and end of selected horizontal curve were known, radius and superelevation of curve obtained from RSP were easily compared with designed values. Evaluations in this curve showed that RT profile is a suitable parameter to find the start and end of transition and horizontal curve. This issue is of great importance in roads that were constructed many years ago and need superelevation evaluation.

Measuring the Superelevation of Andimeshk Ring Curves

In old roads, the radius of horizontal curves may not be clear, so it must be determined by the RSP. Basic steps for evaluating the superelevation in horizontal curves of old roads are as follows:

1. Determination of start and end of the horizontal and transition curves using RSP RT data.
2. Calculation of radius in the circular curves.
3. Calculation of the design superelevation using the radius, coefficient of side friction, and design speed by Eq. (1).
4. Comparing existing road superelevation measured by RSP device with required superelevation calculated in step 3.

Due to the high accuracy of RSP in measuring road geometry parameters (curve radius, cross slope,), this device was used to determine the cross slope of three horizontal curves located in Andimeshk ring of Khuzestan province. This evaluation was performed to determine the existing road superelevation and ensure curves safety. Fig. 7 clarifies the measured RT profile.

The RT diagram in Fig. 7 indicates three separated horizontal curves. Since the RT is negative, all curves are left turn.

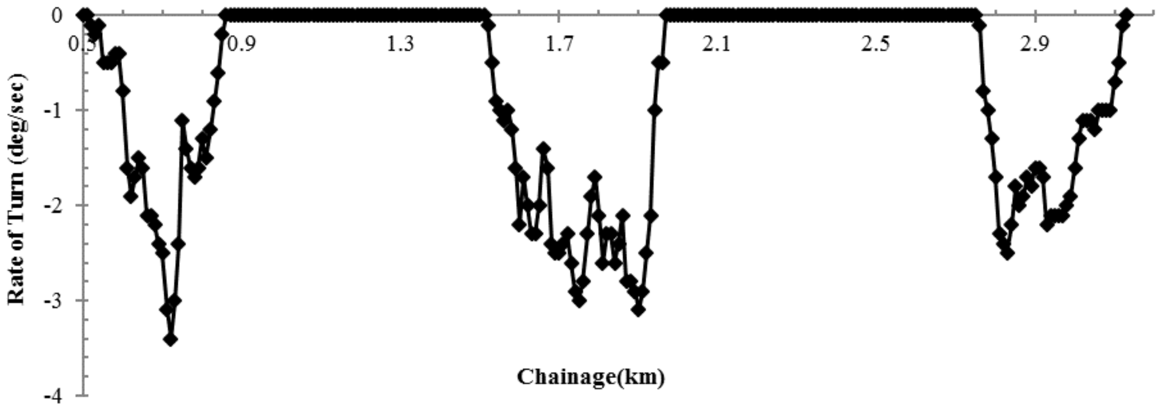

Fig. 7. RT Graph in Andimeshk Ring Horizontal Curves.

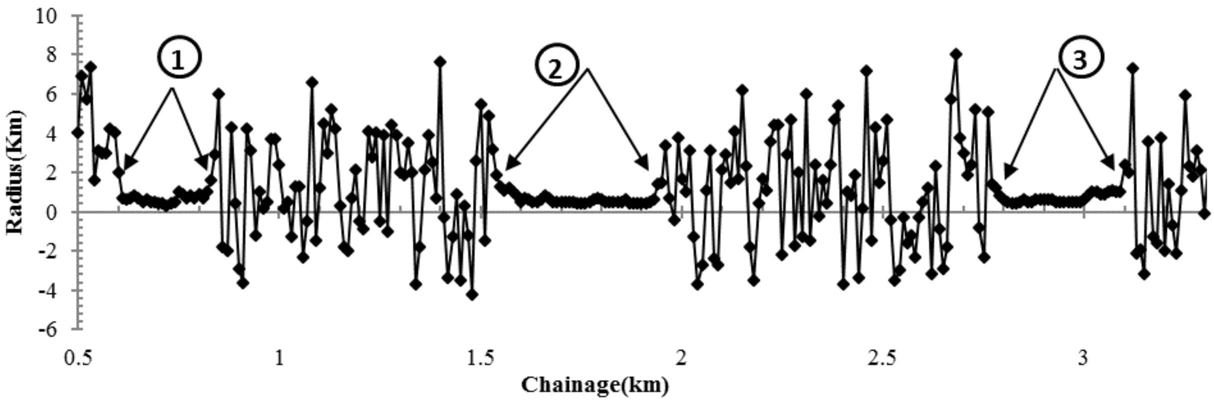

Fig. 8. Radius of Andimeshk Ring Horizontal Curves.

In Fig. 8, the radius graph for three horizontal curves in Andimeshk ring is plotted. In the straight direction, the amount of measured radius is very high, and it decreases inside the curves. Radius at the start of the curves is high, then becomes constant in the middle part, and increases again at the end of the curves. This confirms the existence of two transition curves at the start and end of the curves as well as a circle curve in the middle part. In Table 5, radius of horizontal curves in Andimeshk ring was calculated based on the harmonic mean concept.

Fig. 9 presents the cross slope graph measured by RSP. Cross slope in the curves (superelevation) are positive since the curves are left turn. On the other hand, to secure safety, the required superelevation is calculated by means of design speed of 110 km/h and side friction coefficient of 0.12 (according to Iranian code No.415, the value corresponds to design speed) with Eq. (1). In order to assess the safety of curves, a comparison was drawn between the measured superelevation by RSP and the designed one resulted from Eq. (1) (Table 6).

Table 6 shows that curve numbers 1 to 3 have 3.5, 4.5, and 4.5 percent superelevation shortages, respectively. Therefore, in order to ensure the safety of curves, a new posted-speed should be assigned before the curves according to the last column of Table 6. Another solution is asphalt overlaying to modify curve superelevation. While the road width is 11 meters in the curve, a 50 cm height difference must be provided between both sides of the curve. This issue takes place in cases when superelevation was not performed from the subgrade during road construction, or when changes occurred due to asphalt overlaying in road maintenance periods.

Table 5. Radius of Andimeshk Ring Horizontal Curves.

Row	Curve Length (m)	Average Curvature (1/m)	Radius (m)
1	130	0.00198	505
2	320	0.00199	503
3	200	0.00190	526

Summary and Conclusion

In this research, RSP was used to measure profile of pavement cross slope and RT along every 5 meters of curve length. The start and end of curves, which were identified using RT profile, had a key role in evaluating curve superelevation. Curve superelevation and radius were then determined in specified region. A newly constructed road in Shahroud-Miami was selected to confirm RSP geometric data because curve design parameters were available from SRTA. Three horizontal curves in Andimeshk ring were then evaluated according to findings from the Shahroud-Miami roadway. The obtained results are as follow:

1. Construction or maintenance tasks could change the geometric properties of curves, especially superelevation. Thus, curves need to be evaluated with efficient and appropriate devices. RSP is capable of measuring RT and cross slope profiles quickly (up to 110 km/h) at 5 meter intervals. Therefore, it is a suitable device to assess curve superelevation quickly.

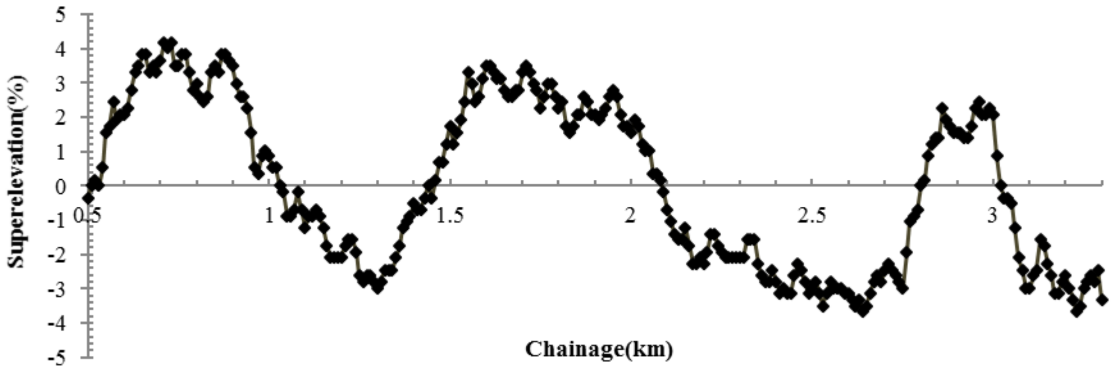

Fig. 9. Cross Slope Graph in Andimeshk Ring Curves.

Table 6. Comparing Measured and Design Superelevation in Andimeshk Ring Curves.

No.	Curves Length (m)	Curves Radius(m)	Superelevation (%)		Superelevation Shortage (%)	Posted Speed Limit (km/h)
			Measured RSP	Design (Eq.(1))		
1	130	505	3.5	7	3.5	100
2	320	503	2.5	7	4.5	95
3	200	526	1.5	6	4.5	95

2. The RT profile could be used to identify the start and the end points of the curves which is of great importance in assessing a curve's superelevation by RSP device.
3. A good agreement was found between cross slope measured by RSP device and designed ones taken from SRTA in Shahroud-Miami curves in both transition and circle parts.
4. Proposed methods to evaluate a curve's superelevation must be performed in two important steps. First is to determine the start and the end of curve using the RT profile, and second is to calculate radius and superelevation based on harmonic and arithmetic mean, respectively, within the curve. The resulting superelevation is then compared with the designed one obtained using curve radius, side friction, and design velocity.

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