Automated pavement horizontal curve measurement methods based on inertial measurement unit and 3D profiling data

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Pavement horizontal curve is designed to serve as a transition between straight segments, and its presence may cause a series of driving-related safety issues to motorists and drivers. As is recognized that traditional methods for curve geometry investigation are time consuming, labor intensive, and inaccurate, this study attempts to develop a method that can automatically conduct horizontal curve identification and measurement at network level. The digital highway data vehicle (DHDV) was utilized for data collection, in which three Euler angles, driving speed, and acceleration of survey vehicle were measured with an inertial measurement unit (IMU). The 3D profiling data used for cross slope calibration was obtained with PaveVision3D Ultra technology at 1 mm resolution. In this study, the curve identification was based on the variation of heading angle, and the curve radius was calculated with kinematic method, geometry method, and lateral acceleration method. In order to verify the accuracy of the three methods, the analysis of variance (ANOVA) test was applied by using the control variable of curve radius measured by field test. Based on the measured curve radius, a curve safety analysis model was used to predict the crash rates and safe driving speeds at horizontal curves. Finally, a case study on 4.35 km road segment demonstrated that the proposed method could efficiently conduct network level analysis.

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1. Introduction

Horizontal curves serve as smooth transitions between tangent sections of pavements, and are complex but unavoidable features for all roads (Calvi, 2015; Othman et al., 2012). Most crash studies indicated that road curves present a higher crash risk and a larger proportion of severe crashes than straight segments (Gibreel et al., 2001; Othman et al., 2005). As reported by the Federal Highway Administration (FHWA) Office
of Safety, 27% of fatal crashes occurred on horizontal curves in the years of 2006–2008 (FHWA, 2010). Therefore, determining curve geometry and its effects on accidents is one of the critical steps in safety studies of pavements on curves.

Previous studies and efforts show that radius measurement methods of pavement horizontal curves can be grouped into two categories: manual methods and automated methods. The manual methods include chord length method (Easa, 1994), compass method and plan sheet method (Carlson et al., 2005). However, the manual methods are time consuming, labor intensive, not suitable for network-level survey, and present a potential hazard for field operators (Chen and Hwang, 1992; Carlson et al., 1996; Dong et al., 2007; Dubeau et al., 1995; Easa, 1994). Therefore, researchers or agencies are motivated to develop methods that can automatically perform horizontal curve identification and radius measurement.

Othman et al. (2012) devised an approach to derive path radius and identify start-end points of horizontal curves by using field operational test data. However, the field operational test needs to be conducted multiple times on one curve for accurate measurement. As a result, this method requires extensive labor and is not suitable for network-level survey.

In the study of Carlson et al. (2005), a ball bank indicator (BBI) was employed to measure the lateral acceleration, and the curve could be back-calculated based on the point-mass equation and radian measures. This method is based on the assumption that effects of vehicle body roll on measurements can be negligible, therefore the measurement accuracy is subjective to body roll angle. Moreover, this method is not suitable for network level survey since its implementation requires the establishment of the PC and PT stations on site prior to the test and the testing vehicles must be driven at a constant speed throughout the curve.

Imran et al. (2006) and Bogenreif et al. (2012) presented a method of incorporation global positioning system (GPS) information into a geographic information system (GIS) for the calculation of the radius, length, spiral length, and vehicle position of horizontal curves. In this method, the curve radius was computed by automatically extracting the arc and chord length of the curve from a GIS map. However, extensive labor is still required for this method, which hinders its application to network-level survey.

Few studies have been conducted on curve radius measurements at network levels since the previous data acquisition systems are incapable of continuously measuring required data sets at highway speed and most data processing systems cannot fulfill automated identification of the start and end points of curves (Ai and Tsai, 2014; Easa et al., 2007; Vatankhah et al., 2013).

This study presents an automated method for horizontal curve identification and radius measurement for network level application. To achieve this goal, the digital highway data vehicle (DHDV) is used to continuously collect inertial measurement unit (IMU) data, global positioning system (GPS) data, and distance measurement instruments (DMI) data, and 3D profiling data at high speeds up to 100 km/h. The horizontal curve is automatically identified based on the change of heading angle from IMU, and the curve radius is calculated by three methods, namely kinematic method, geometry method, and lateral acceleration method. The flowchart of the automated horizontal curves measurement is shown in Fig. 1. Finally, a 4.35 km pavement section with five horizontal curves is chosen to explore the effectiveness of the proposed automation in horizontal curve investigation and curve safety analysis. Results indicate the presented approach is capable of rapidly analyzing crash potentials, estimating safe driving speeds at horizontal curves, and identifying the hazardous curves.

## 2. Data acquisition

### 2.1. Digital highway data vehicle (DHDV) with PaveVision3D

DHDV, developed by the WayLink Systems Corporation with collaborations from the University of Arkansas and the

![Flowchart of automated horizontal curve measurement.](image-url)
Oklahoma State University, has been evolved into the sophisticated system to conduct full-lane data collection on roadways at highway speed up to 100 km/h. With the latest PaveVision3D Ultra (3D Ultra in short), the resolutions of surface 3D data are about 0.3 mm in vertical direction and 1 mm in the longitudinal and transverse directions, all achieved at 100 km/h data collection speed. Fig. 2(a) shows the exterior appearance of the DHDV equipped with the 3D Ultra technology. With the high power line laser projection system and custom optic filters, DHDV can work at highway speed during daytime and nighttime and maintain image quality and consistency (Wang et al., 2011). The camera and laser working principle is shown in Fig. 2(b). In this study, the 3D transverse profiling data collected by this equipment is used for super-elevation calibration.

2.2. Inertial measurement unit (IMU)

The inertial measurement unit (IMU) is a self-contained sensor consisting of accelerometers and fiber-optic gyroscopes. The physical principle of this type of gyroscope operation is analogous to the doppler effect, which involves determination of the phase shift between two counter propagating light beams (Luo et al., 2014). The IMU is integrated and synchronized into the DHDV vehicle.

3. Methodology

Three methods, namely kinematic method, geometry method, and lateral acceleration method, are employed to compute horizontal curve radius based on both IMU and 3D transverse profiling data. To examine the effectiveness of the three methods in radius calculation, the ground truth measured by field test is used.

3.1. PC and PT identification method

The start-end points (PC and PT) of a curve are critical for curve identification and length calculation, and can be determined by the variation of heading angles. Firstly, the differences of heading angles at two adjacent points are calculated. If the calculated differences are greater than “m” (a threshold to determine whether the point is the candidate curve point or not), the two points can be considered as the candidate curve points. Secondly, the number of consecutive candidate curve points are determined. If the number is greater than “k” (a threshold to determine whether the segment is the curve or not), these points can be considered as the curve points. As a result, the first and the last points of the curve points are considered as the PC and PT of the curve.

3.2. Kinematic method

The kinematic method uses the velocity in the longitudinal direction and the centrifugal acceleration of survey vehicle for curve radius calculation (Beer and Johnston, 1977), as Eq. (1) shows. Both “v” and “a” are directly obtained based on the output data from the IMU: “v” is the north velocity in IMU data set, and “a” is the transverse acceleration in IMU data set.

\[ R = \frac{v^2}{a} \]  

where R is the curve radius (m), v is the velocity of the vehicle in the longitudinal (body x) direction measured by IMU (km/h), a is the centrifugal acceleration of the vehicle on a horizontal plane measured by IMU (m/s²).

3.3. Geometry method

The geometry method plots the actual vehicular horizontal trajectory using the velocity vector and then determines the radius (Randeniya, 2007), as in Fig. 3 and Eqs. (2)–(11). Due to the high frequency of data collection with 200 Hz, the error associated with the linear approximation can be ignored for the vehicular horizontal trajectory. The longitudinal displacement of the vehicle between two consecutive data points i and (i + 1) can be calculated by Eq. (2) using the average velocities at those two points. In this method, the vehicle trajectory on the x–y plane is described by the function \( y = f(x) \), and the curve radius can be calculated by Eq. (3). Since x and y coordinates are found in terms of time as discrete quantities (Eqs. (4) and (5)), the second order forward difference formula can be obtained by Eqs. (6)–(9), and the numerical forms of the derivatives can be produced by Eqs. (10) and (11).

\[ ds = \frac{1}{2} (v_i + v_{i+1}) dt \]  

\[ R = \left(1 + \left(\frac{d^2 y}{dx^2}\right)\right)^{3/2} \]  

Fig. 2 – Photographs of DHDV. (a) DHDV exterior appearance. (b) PaveVision3D working principle.
transverse slope, which is based on the assumption that the vehicle floor is parallel with pavement surface during traveling. However, in real world the vehicle floor is always unparalleled with pavement surface during traveling due to the following reasons: 1) uneven gravity distribution of the vehicle; 2) vibration of the vehicle during traveling; 3) pavement surface condition. Therefore, the IMU and 3D profiling technology are combined in this study to measure the super-elevation. The “true” super-elevation of the pavement can be approximately determined with two et al., parameters: the tilt of the vehicle floor and the slope of pavement surface captured by 3D cameras (Luo et al., 2014). As Fig. 4 shows, the IMU provides angle of the vehicle relative to a level datum, as shown by angle $\theta$. $\gamma$ is the angle of the vehicle relative to the pavement, which can be obtained by Eq. (13). The “true” super-elevation can be calculated by Eq. (14). However, in real world the angle $\theta$ and $\gamma$ are very small, so the super-elevation can be directly considered as the difference in slope of $\theta$ and slope of $\gamma$, as Eq. (15) shows (Mekemson and Gagarin, 2002).

$$\gamma = \arctan\left(\frac{y_R - y_L}{L}\right)$$

(13)

$$e = \tan(\theta) + \tan(\gamma)$$

(14)

$$e = \frac{\tan(\theta)}{\tan(\gamma)}$$

(15)

where $e$ is the angle of cross slope/super-elevation (degree), $\gamma$ is the body roll angle of vehicle (degree), $\theta$ is the IMU roll angle (degree), $L$ is the distance between left and right laser (m), $y_L$ is the vertical distance from left sensor to the pavement surface (m), $y_R$ is the vertical distance from right sensor to the pavement surface (m).

3.5. Chord offset method

The chord offset method is a common method used in the field for roadway curve radius calculation. This study uses a tape held on either end at the precise edge of the road way, while a carpenter’s rule is used in the middle of the tape to measure the distance between the edge of the tape and the edge of the roadway. The curve radius that can be obtained by Eq. (16) and measured by this method is considered as ground truth in this study.

$$R = \frac{u^2}{127(e' + a)}$$

(12)

where $e'$ is the super-elevation (m/m).

For the super-elevation measurement, the roll angle measured by IMU is widely accepted to represent pavement

3.4. Improved lateral acceleration method

The lateral acceleration method is based on the equation as used in the BBI method (Eq. (12): point-mass equation) for curve radius calculation (Carlson and Mason, 1999, Zhou and Hawkins, 2014). Different from BBI method, the model is improved in this study: IMU is used to measure the lateral acceleration, vehicle speed, and the super-elevation, and 3D profiling data is used to calibrate the super-elevation.

$$R = \frac{u^2}{127(e' + a)}$$

(12)
\[ R = \frac{L_1}{8M} + \frac{M}{2} \] (16)

where \( L_1 \) is the chord length (m), \( M \) is the offset distance (m).

### 4. Case study

#### 4.1. Test site

A 4.35 km long and 3.65 m wide flexible pavement section located on Spavinaw, Oklahoma is selected as the test site in this study. As Fig. 5 shows, there are five simple horizontal curves located on test section. This test section starts from the location (Latitude: 36.329175, Longitude: -95.081696), and ends with the location (Latitude: 36.351066, Longitude: -95.062796), as Table 1 illustrates.

#### 4.2. Data sample

The 3D profiling data collected by DHDV is stored in computer hard disk in the form of raw images with the size of 4096 pixel in lane-width by 2048 pixel in the longitudinal direction. The IMU system has the high frequency of 200 Hz during data collection. The two types of data (3D data and IMU data) can be automatically matched by DMI pulses, since they are shown in two types of data sets. In this study, one raw image for the 3D profiling data or the average value of 1 IMU data records is considered as a sample, and the sample length is 2.28 m, as in a single raw 3D data file. Based on Eq. (13), the slope of the 3D profiling data represents the vibration angle of vehicle. The real cross slope/super-elevation is equal to the raw cross slope/super-elevation minus the slope of the 3D profiling data, as shown in Eq. (15). Table 2 shows the example of the IMU data for curve radius calculation. Fig. 6 shows the super-elevation of five curves: the orange line represents the raw data; and the green line represents the calibrated super-elevation. By comparing the raw data and the calibrated super-elevation, it is found that the noise (e.g., the abrupt drop) derived from the vehicle body roll is suppressed after calibration.

#### 4.3. Curve identification and curve length measurement

In this study, three “\( m \)” (0.1, 0.3, and 0.5) and two “\( k \)” (5 and 10) are used to determine the appropriate thresholds for curve identification. Fig. 7 shows the measured heading angles at the five curves, in which six threshold combinations are examined to determine the PC and PT of the curves. Generally, the small “\( m \)” would enlarge the lengths of identified curves due to the influences of the vehicle wandering, while the large “\( m \)” would

### Table 1 – Summary of test site.

<table>
<thead>
<tr>
<th>Location</th>
<th>Starting point</th>
<th>Ending point</th>
<th>Test length (km)</th>
<th>Lane width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spavinaw, Oklahoma</td>
<td>Latitude: 36.329175</td>
<td>Latitude: 36.351066</td>
<td>4.35</td>
<td>3.65</td>
</tr>
<tr>
<td></td>
<td>Longitude: -95.081696</td>
<td>Longitude: -95.062796</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 – Example of IMU data for curve radius calculation.

<table>
<thead>
<tr>
<th>( \alpha_{\text{heading}} ) (degree)</th>
<th>( \alpha_{\text{Roll}} ) (degree)</th>
<th>Speed (km/h)</th>
<th>N_Vel (m/s)</th>
<th>E_Vel (m/s)</th>
<th>L_Acc (m/s^2)</th>
<th>T_Acc (m/s^2)</th>
<th>D_Acc (m/s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,379,803</td>
<td>88.06</td>
<td>1.48</td>
<td>53.37</td>
<td>1.59</td>
<td>78.25</td>
<td>0.18</td>
<td>0.03</td>
</tr>
<tr>
<td>7,379,803</td>
<td>88.06</td>
<td>1.49</td>
<td>53.36</td>
<td>1.60</td>
<td>78.24</td>
<td>-0.80</td>
<td>0.50</td>
</tr>
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<td>7,380,445</td>
<td>88.07</td>
<td>1.50</td>
<td>53.36</td>
<td>1.60</td>
<td>78.24</td>
<td>-0.30</td>
<td>-0.10</td>
</tr>
<tr>
<td>7,381,089</td>
<td>88.07</td>
<td>1.53</td>
<td>53.37</td>
<td>1.59</td>
<td>78.26</td>
<td>1.23</td>
<td>1.87</td>
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<td>88.09</td>
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<td>1.56</td>
<td>78.26</td>
<td>-0.70</td>
<td>0.69</td>
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<td>7,381,949</td>
<td>88.09</td>
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<td>53.37</td>
<td>1.55</td>
<td>78.26</td>
<td>-0.20</td>
<td>-0.50</td>
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<tr>
<td>7,382,804</td>
<td>88.10</td>
<td>1.59</td>
<td>53.36</td>
<td>1.51</td>
<td>78.24</td>
<td>1.35</td>
<td>2.32</td>
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<tr>
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<td>1.59</td>
<td>53.36</td>
<td>1.52</td>
<td>78.25</td>
<td>0.58</td>
<td>-0.10</td>
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<td>7,383,019</td>
<td>88.10</td>
<td>1.60</td>
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<td>1.53</td>
<td>78.26</td>
<td>0.35</td>
<td>-1.20</td>
</tr>
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<td>7,383,235</td>
<td>88.11</td>
<td>1.61</td>
<td>53.38</td>
<td>1.55</td>
<td>78.27</td>
<td>0.49</td>
<td>-1.10</td>
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<td>1.61</td>
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<td>1.53</td>
<td>78.26</td>
<td>-1.20</td>
<td>0.14</td>
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<td>7,383,881</td>
<td>88.11</td>
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<td>53.36</td>
<td>1.51</td>
<td>78.25</td>
<td>-0.80</td>
<td>3.73</td>
</tr>
</tbody>
</table>

Note: N_Vel: North velocity of vehicle; E_Vel: East velocity of vehicle; L_Acc: Longitudinal acceleration of vehicle; T_Acc: Transverse acceleration of vehicle; D_Acc: Down acceleration of vehicle.
shorten or divide the identified curve due to the negligence of the small heading angle variations (e.g., curve detection using \( m = 0.5 \) in Fig. 7(a)). The threshold \( k \) is used to eliminate the effects of vehicle wandering on curve identification. For example, two curves are detected in Fig. 7(b) using \( m = 0.1 \) and \( k = 5 \). The second detected curve causing by vehicle wandering can be eliminated by using \( k = 10 \). As a rule of thumb, the horizontal curve can be identified when the heading angles linearly increase or decrease. Based on the sensitivity analysis in Fig. 7, the threshold combination of \( m = 0.1 \) and \( k = 10 \) produces the best curve identification and measurement results, based on which the start and end points of a curve can be determined.

At curve 1, the curve points that start with the sample 65 and end with the sample 215 can be obtained, and thus the sample 65 and sample 215 can be considered as the PC and PT of curve 1. In addition, the length of curve 1 can be calculated based on the IMU data interval (0.19 m), with a value of 25.58 m. Similarly, the curve lengths at curves 2, 3, 4, and 5 are computed as well, with values of 15.62 m, 17.34 m, 24.00 m, and 25.15 m, respectively.

### 4.4. Curve radius measurement

Fig. 8 shows curve radius estimated from four abovementioned methods. Herein, the radius of five curves measured by field test are 168 m, 153 m, 183 m, 143 m, and 111 m, respectively. Analysis of variance (ANOVA) is a common statistical technique for hypothesis testing to check the equality of variations among two or more groups (De Coster, 2002). In this study, this technique is used to test the accuracy of kinematic method, geometry method, and lateral acceleration method for curve radius measurement, and the curve radius measured by field test is considered as control.
variable. There are five distinct levels \((a)\) in scale for \(p\)-values: \(0.001, 0.001, 0.01, 0.05, 0.1\), and \(0.1\) (Qu et al., 2014). The mostly widely used distinct level, \(a = 0.05\), is selected in this study. The significant difference is considered as “existence” if the distinct level is smaller than 0.05.

Table 3 shows the ANOVA test results for three methods. According to the distinct level \((a = 0.05)\), the difference between the control variable and the measurements of three methods are not significant, which means all of three methods have good accuracy in curve radius measurement. It can be observed that the radius calculated from kinematic method has the least difference with the ground truth, and followed by is geometry method and lateral acceleration method.

### 4.5. Curve safety analysis

A curve safety analysis model developed by Fitzpatrick et al. is applied to predict the safe driving speeds and crash rates of the curves. This model is used to describe the relationships between curve radius and crash frequency based on the crash data on two-lane rural highways (Fitzpatrick et al., 2000). Eqs. (17)–(19) are used to compute the total curve crash rates and safe driving speeds. In this study, the tangent speed limit (105 km/h) of the test site is considered as the 85th percentile tangent speed of passenger cars.

\[
\text{CR} = \text{CR}_b \times \text{AMF}_{sr}
\]  
\[
\text{AMF}_{sr} = e^{0.078(V_{t,85,pc} - V_{c,85,pc})}
\]  
\[
V_{c,85,pc} = 104.77 - \frac{3576}{R}
\]

where CR is the total curve crash rate (crashes/million-vehicle-km, crashes/mvk), \(\text{CR}_b\) is the base crash rate (crashes/mvk), \(\text{AMF}_{sr}\) is the accident modification for curve speed reduction, \(V_{t,85,pc}\) is the 85th percentile tangent speed of passenger cars (km/h), \(V_{c,85,pc}\) is the 85th percentile curve speed of passenger cars (km/h).

The safety evaluation results at the five curves are shown in Table 4. The safe driving speeds at the five curves are
estimated to be around 80 km/h, and the estimated crash rates at five curves are ranked as follows from low to high: curve 3, curve 1, curve 2, curve 4, and curve 5.

5. Conclusions

An automated method for curve identification and radius measurement with IMU and 3D profiling data is proposed in this study. This method supports network level survey, and

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**Fig. 8** – Curve radius calculated from four methods at 5 curves. (a) Curve 1. (b) Curve 2. (c) Curve 3. (d) Curve 4. (e) Curve 5.

<table>
<thead>
<tr>
<th>Method</th>
<th>t-value</th>
<th>p-value</th>
<th>Significant difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic method</td>
<td>0.34</td>
<td>0.7357</td>
<td>No</td>
</tr>
<tr>
<td>Geometry method</td>
<td>0.57</td>
<td>0.5703</td>
<td>No</td>
</tr>
<tr>
<td>Lateral acceleration</td>
<td>0.69</td>
<td>0.4057</td>
<td>No</td>
</tr>
</tbody>
</table>
incorporates various data sources into the existing models. For the data collection and processing, this study incorporate IMU data, 3D profiling data, and DMI data for horizontal curve measurement. The transverse profiling data from DHDV is combined with the roll data from IMU to produce the super-elevation data. It is found that the noises caused by the testing vehicle body roll are suppressed after the described calibration is applied.

For the curve identification, the change of heading angles are used to automatically determine the PC and PT of horizontal curves, and curve lengths can be computed as well based on the number of data samples or image files between PC and PT. For the curve radius measurement, three approaches including kinematic method, geometry method, and lateral acceleration method based on IMU and 3D profiling data are employed to automatically determine the radius of horizontal curves, and the ground truth of curve radius is obtained by field test. ANOVA test results indicate all three methods have good accuracy in curve radius measurement, among which the result from kinematic method has the least difference with the ground truth. For the case study, the pavement segment with five horizontal curves is selected to illustrate an application of the Fitzpatrick's model for conducting curve safety analysis on horizontal curves. In the future, more experimental tests are recommended on various horizontal curve types including the spiral curve, compound curve, and reverse curve to determine the effectiveness of the proposed method in radius measurement and safety analysis for a broad range of curves.

### Table 4 — Curve safety evaluation for test sites.

<table>
<thead>
<tr>
<th>Curve</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{AS,pre}$ (kn/h)</td>
<td>83.47722</td>
<td>81.38989</td>
<td>85.22237</td>
<td>79.75505</td>
<td>72.54410</td>
</tr>
<tr>
<td>$R$ (m)</td>
<td>168</td>
<td>153</td>
<td>183</td>
<td>143</td>
<td>111</td>
</tr>
<tr>
<td>$AMFR_p$</td>
<td>5.358996</td>
<td>6.306550</td>
<td>4.676991</td>
<td>7.164268</td>
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<tr>
<td>CR (crashes/mvk)</td>
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<td>2.648751</td>
<td>1.964336</td>
<td>3.008992</td>
<td>5.280704</td>
</tr>
</tbody>
</table>

**REFERENCES**


