Accuracy Limits of Geometric Analysis Based on Data Collection Vehicles

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ABSTRACT

Many techniques are currently available for measurement and interpretation of the geometric features of the roadway. Traffic speed, pavement survey vehicles such as the ARAN, are readily equipped with highly accurate location referencing equipment, and have proven to be a time and cost effective means of collecting horizontal and vertical curvature parameters.

The accuracy of a survey vehicle's combined Geographical Positioning System (GPS) and Inertial Navigation System (INS) allow for the very effective measurement of the driven path (reproduction of latitude, longitude, elevation and heading) to be collected at traffic speed, and under a range of satellite interference conditions. The real world accuracy of an ARAN with combined GPS and INS system allows for a trail with a positional accuracy of under 0.5 m to be reported.

Curve-fitting algorithms, used to post process collected position data, is highly capable of interpreting the location coordinates into paths of correctly assigned tangent sections and circular curves / parabolas along horizontal and vertical alignments.

Using traffic speed, survey vehicles for the collection of horizontal alignment data, factors such as vehicle wander within lanes, lane changes, and lane closures have the potential to affect the integrity of geometric data. The level of error induced by these movements is very dependent on the arc radius and arc length. For shorter arc lengths, the potential curve radius error from vehicle wander (in excess of 5% for small radii curves) becomes more of concern as curve deflection increases. Consequently, and when considering the sensitivity of crash frequency based on the percent error in the prediction of curve radius, just care is recommended when applying design restrictions, such as minimum radius and design speed, for curves of shorter curve arcs.

This curve alignment process of combining data collected by traffic speed, survey vehicles with curve fitting post-processors, has been found to be very effective means of measuring a range of geometric policies. When planning roadway geometric surveys it is important to understand the purpose and accuracy level necessary for the different data uses.

INTRODUCTION

The geometric design of a roadway is based on many factors to ensure the safety and comfort for transporting both people and goods. Obtaining up-to-date geometric data of a network is important due to changes in standards, widening of roads, increases in traffic, and sometimes the adjustment of speed limits. As a part of routine pavement management surveys, the driven path of many roads and highways are traced to allow for the analysis of many geometric attributes. The GPS trail of such traffic speed survey vehicles can be used to estimate the horizontal and vertical curves of the road along with grade and cross-slope.

This paper investigates the associated level of accuracy contributed to the semi-automated collection of roadway horizontal alignment using traffic speed vehicles fitted with Global Positioning System (GPS) and Inertial Navigation System (INS). The use and accuracy of the traffic speed collection vehicles fitted with GPS / INS systems for the collection of roadway alignments at a network level have become increasingly common due to the followings reasons:

- Recent and continual improvements in the accuracy of non-military GPS applications;

- Efficiency and cost effectiveness gains in network collection of horizontal alignments when compared to alternative collection means;
- Elimination of the health and safety implications of measuring horizontal curvature parameters statically (along the roadside) or at collection speeds that are considerably lower than that of the traffic speed, and;
- The requirement of road network operators to have an up-to date, accurate and complete reference database of their horizontal and vertical alignment parameters for a given network.

Pavement monitoring vehicles, such as the Automatic Road Analyzer (ARAN), which are primarily used for the collection of pavement condition parameters, typically use GPS / INS systems to provide position referencing data to its pavement monitoring subsystems. In order to assess the competency of an automated vehicle equipped with GPS / INS system to collect accurate and repeatable curvature alignment data, the following areas are investigated in turn:

- An introduction into typical roadway curves and geometric parameters.
- A review of the technologies available for the collection of horizontal alignment parameters, particularly curve radius and length.
- A case study assessing the typical accuracy and repeatability of a GPS / INS system in the collection of horizontal curvature alignment parameters.
- The role of post-processing algorithms in mitigating collection errors associated with the collection of horizontal and vertical curvature parameters using high speed collection survey vehicles.
- The influence of the vehicle driven path, a product of road line-markings and driver behavior, on the prediction of horizontal curve radius using GPS / INS survey vehicles.

Introduction to Curves and Geometric Parameters

During the geometric design phase of roadways, a path is selected to meet a range of criteria such as reducing the amount of material required on site, land availability issues, and a range of safety oriented concerns. To simplify the layout of the road, horizontal and vertical alignments are often described using a series of straight tangents and curves.

To model roadway curves, a simple circle is most commonly used for smaller curves where design speeds are typically low. However, many curves are built on larger speed facilitating spirals, whereby the curvature increases steadily to a curves midsection, followed by decreasing curvature, allowing drivers to have a more natural and comforting transition through a curve.

Some agencies also have combinations of curves that they use to describe the layout of the road. The reverse curve, which consists of two back to back curves with opposite directions of curvature, is relatively common in areas where the location of road is based on physical features such as rivers and hills. Compound curves are described as back to back curves in the same direction of curvature, but with different curve radii. Figure 1 illustrates the alignment of these horizontal curve types.

Vertical curves are similar to horizontal curves, but typically do not have as many different combinations. Peaks and valleys are easier to identify and tangents tend to be longer for vertical curves. For vertical curves, the arcs are more commonly modeled as parabolas rather than as circular arcs so they better match the conditions of the existing terrain. Figure 2 illustrates the alignment of typical vertical curve types.

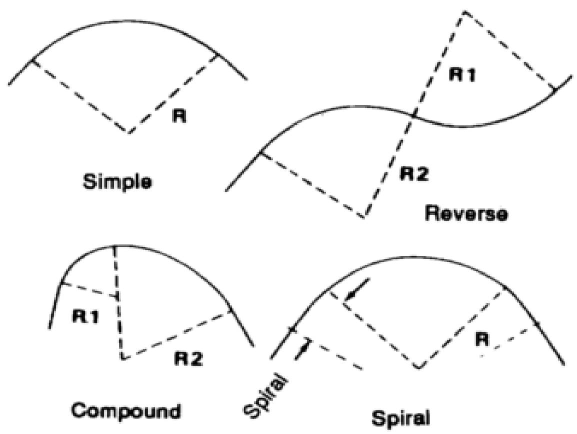

Figure 1: Horizontal Curve Types (1)

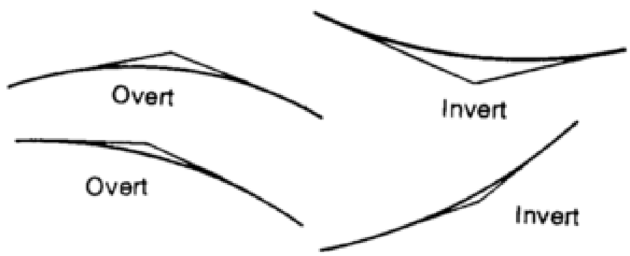

Figure 2: Vertical Curve Types (1)

The other features that are commonly measured include grade and cross-slope. These parameters measure the instantaneous layout of the road at any location. Grade is the measure of longitudinal road slope (Figure 3). Grade is an important parameter along hilly and mountainous terrain, in both ascending and descending directions, to ensure that large and heavy vehicles have adequate power to go up the hill and adequate braking power while going down hills. Transitions in grade are also important in many cases for overt changes to ensure safe sight distances due to the crest of the road.

Cross-slope is a measure of the transverse slope of the road (Figure 3). Cross-slope conformance is necessary to ensure adequate drainage of the road surface. Typical highway conditions suggest a cross-slope of 2% (change in height divided by pavement width) to ensure that water drains properly to the side of the road. If the cross-slope is inadequate, it may cause water to pool in the active traffic lanes, which may cause hydro planning and can become a serious risk to the safety of the travelling public. However, for high speed facilities and some tighter turns such as ramps, the cross-slope is modified to reduce the horizontal forces in turns. The transitions zones in these areas can have cross-slopes that change from left leaning to right leaning (or vice versa) which will have some transition area with low cross-slope, presenting increased risk to drivers due to the effects of hydroplaning.

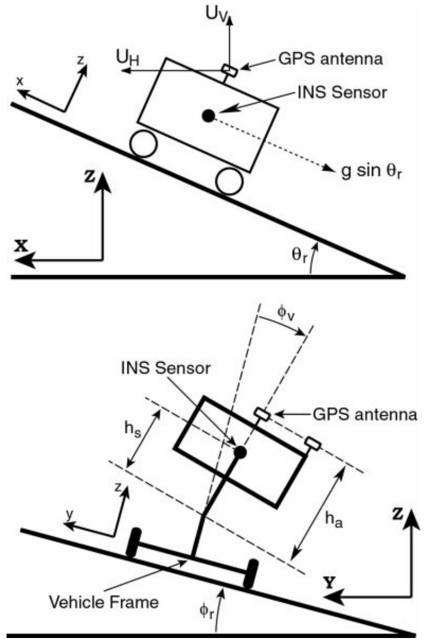

Figure 3: Grade (top) and cross-slope (bottom) (2)

COLLECTION OF HORIZONTAL ALIGNMENT PARAMETERS

Numerous techniques are currently used to measure roadway horizontal curvature (radius and deflection angle) and geometry (super-elevation). These methods include static, labor intensive methods such as total station and chord measurements, aerial photography and vehicle based measurements at or below design speed. Many considerations need to be made in the selection of an appropriate survey method including the expected accuracy of the technique, its cost to implement, associated potential safety risks in its execution, and the time required to collect curve attributes.

Total station and chord measurement methods require physical measurements within the roadway environment which are costly, time consuming and potentially dangerous for field testing personnel. Aerial photography techniques are capable of determining attributes such as curve radius and deflection angle but are unable to calculate other attributes such as grade and super elevation.

Obtaining curve dimensions from as-built plans is one of the most accurate means of determining geometric characteristics. However, such plans are not always available or consistent with the field conditions, especially for older pavements, and further require trained personnel for their interpretation. There had existed a need for the accurate measurement of horizontal curve geometry in a manner that is repeatable, unbiased, time and cost effective, and which does not place personnel in unnecessary health risks. (3) (4)

With the development of the Geographic Positioning System (GPS) and its incremental improvements in accuracy, a new technique became available to measure roadway curvature and geometry characteristics at or near design speeds, with a higher degree of accuracy when compared to alternative, on-site measurement techniques. (3) (4) (5)

Carlson et. Al (3) experimented with numerous technologies for the measurement of curve radius. From the analysis of 28 horizontal curves on two lane roadways in Texas, the most precise (least relative error) of these techniques (Figure 4) were the plan sheets (4.46%) and GPS method (2.65%).

Pratt et. Al (4) investigated the accuracy of a GPS and Ball Bank Indicator (BBI) system, once post-processed using a radius estimating algorithm, on four curves with known (ground truth) curvature. The GPS / BBI system was found to be capable of measuring curve radius with an error of five-percent or less to the known, true radius. However this study was undertaken at vehicle speeds of 45mph (72 km/h), less than most highway speeds.

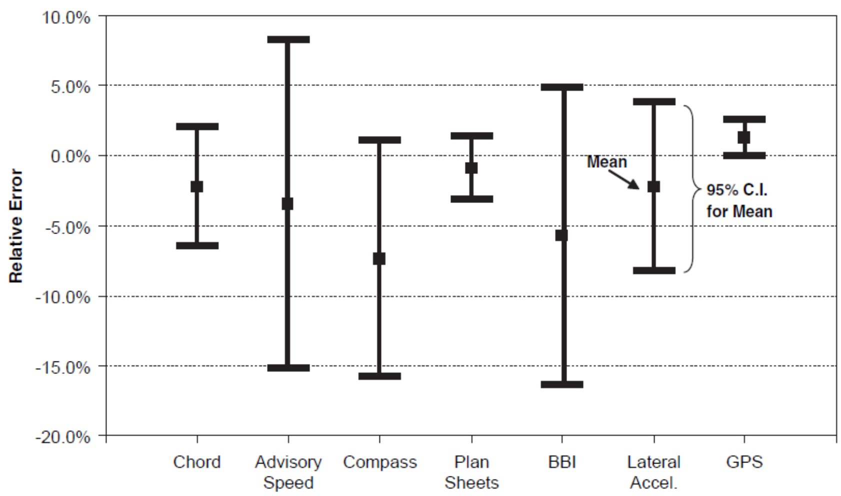

Figure 4: Relative error associated with curve radius measurement techniques (3)

Hans et. Al (5) also investigated the accuracy of a GPS system in the measurement of horizontal road curvature for a network level project of 435 known curves of at least 50m in length, collecting GPS coordinate data at 10m intervals. Comparing as-built curve radius to the radius calculated using the circular regression model (using polylines developed by GPS data for the 435 curves), a coefficient of determination (R-squared) of 0.93 and root mean square percent error of 16.3% resulted.

Hans et. Al (5) went on to assess the sensitivity of error in the prediction of curve radius on the percent change in vehicle crash frequency. This relationship was assessed with use of equations 10-2, 10-6 and 13-5 of the AASHTO Highway Safety Manual (6). These equations predict the crash modification factor using a range of curve attributes including the influence of a curves' radius and length, in addition to whether such curves contained transitioning radii. Figure 5 illustrates the results of this analysis for a range of curve radii (feet), demonstrating an increasing influence of crash frequency with increasing percent error in the prediction of curve radii.

Some limitations do exist for GPS inertial methods such as the variation between curve radius measured along the vehicle path and the radius of the geometric radius of the curve (4), measured to the inside of the inner most lane (8). The variation between these two can be influenced by the direction driven, which as an example can differ by a kappa statistic (a value of 0.90 being an excellent correlation and a value of 0.75 being a good correlation) of k=0.94 in one direction, and k=0.70 for the opposite direction (7). Other influential factors can include lane markings, the driven lane for a given direction and driver behavior such as wander within a lane.

Another potential limitation associated with vehicle collection of curve data includes the loss of signal between satellites and the vehicles GPS receiver. Depending on the quality of the back-up inertial system (INS), this will result in depleting accuracy of vehicle position with increasing time of lost GPS signal.

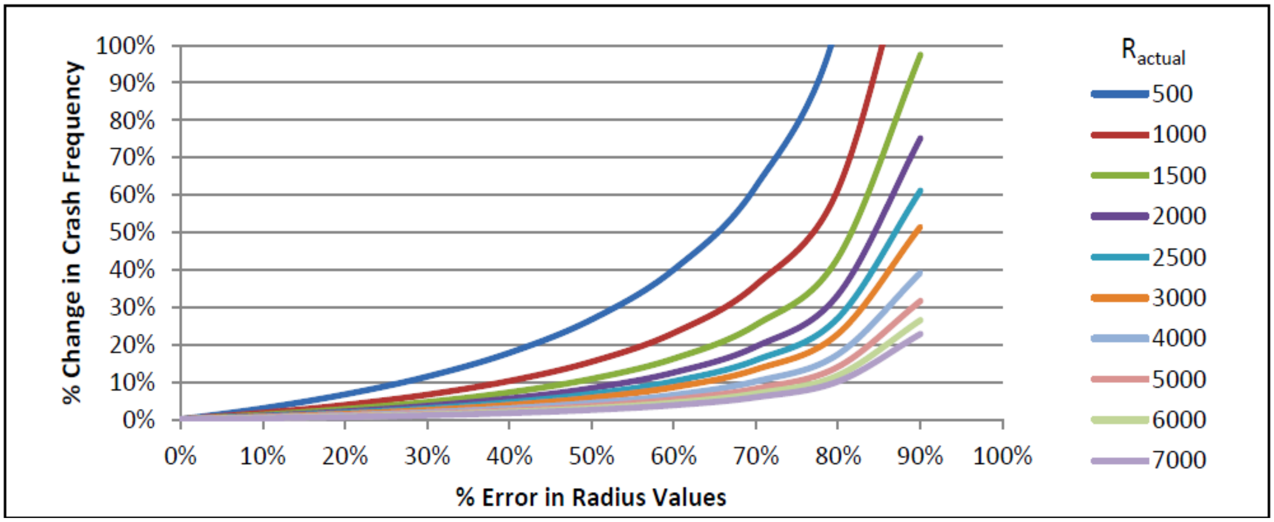

Figure 5: Sensitivity of crash frequency to the percent error in the prediction of curve radii (5)

The designs of horizontal curves along a roadway are not always comprised of simple, circular curves of consistent radius. Transition curves are the combination of two or more curves aligned in a manner to provide a gradual change in the alignment radius (8). A spiral curve (typically used for highway on-ramps) is a single curve which progressively increases and decreases the radius along the curve length, often in association with change in the super-elevation of the curve, to influence vehicle speed. The existence of transition and spiral curves on the roadway add another degree of complexity to the calculation of curve radius, deflection angle and super-elevation rates.

Pratt et. al investigated the effect of curves with varying radius. They noted that the relationship between the average radii of curves computed using field-measurement techniques (taken at the middle third of a curves length) with the critical (minimum) radii of these curves using the GPS method. Pratt determined that the average, often reported radius does not always align with the critical (minimum) radius. This was found to especially be the case for curves of higher radii, greater than 1500 ft (460m) (4).

COLLECTION OF HORIZONTAL CURVATURE DATA AT HIGHWAY SPEED

When using data collection vehicles for the collection of highway geometry parameters, the most important data collected is the GPS coordinates of the vehicle in terms of the latitude, longitude, and elevation. Using these coordinates, the trail of the vehicle is recorded at regular intervals along the road. This data, when plotted, provides a clear path described as a series of data points (Figure 6). For typical pavement management data collection, GPS coordinates are recorded every 0.02 seconds, which translates to more than 1 reading every 1 m while travelling at highway speeds. This frequency, and the forward movement of the vehicle allows for an accurate interpolation between points for determining coordinates at any point for the travelled path.

This data is however based on the limitations of the technology used to collect it, including a Distance Measurement Instrument (DMI), a GPS receiver, and an Inertial Measurement Unit (IMU). However, for curve fitting, there is a larger interest in any changes in the positional accuracy rather than the absolute accuracy of the position, since consistent offset errors will still provide an accurate shape measurement.

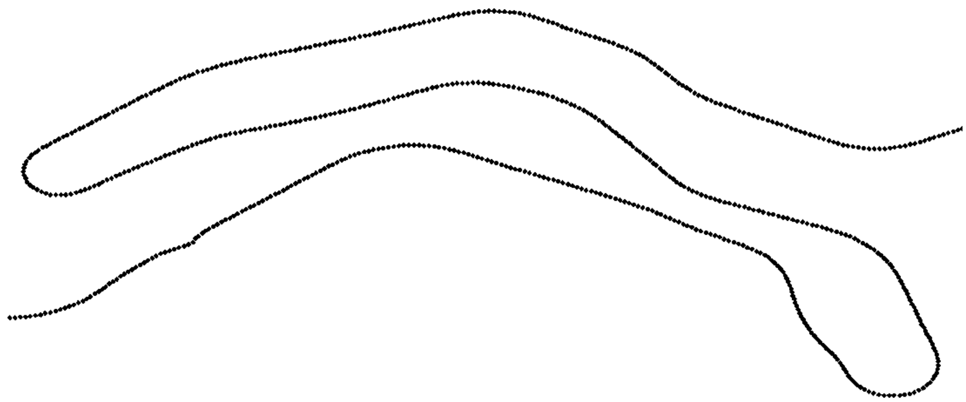

Figure 6: Sample GPS Trail from an ARAN

The collection of roadway horizontal curvature and roadway geometric characteristics (grade, pitch and roll) is completed using a vehicle equipped with the equipment referenced above for the collection of these parameters at highway speeds (in excess of 60mph – 100km/h). While the development of GPS / INS guidance is becoming increasingly common, their reportable accuracy can vary. Typically, such systems should integrate an accurate GPS, numerous 3-axis gyroscopes, inertial accelerometers, and a DMI. The way in which the system operates is to use the gyroscopes, inertial accelerometers and DMI to develop horizontal and vertical station data, using the GPS to perform corrections wherever possible along the roadway.

Pavement data collection vehicles, such as the ARAN, have moved to tightly coupled GPS / INS systems due to the superior correctional service provided by the GPS. To minimize the potential for error, these subsystems utilize real time kinematics (RTK) corrections. Post processing corrections are also made to data including the use of curve fitting algorithms and the use of fixed base station data to make corrections for the known ambiguities of these GPS/ INS systems. Both of these GIS post-processing corrections are described in greater detail in the proceeding sections.

Distance measurement instrument

Using an optical encoder or rotor-pulsar, attached to the driver's side rear wheel, a Distance Measurement Instrument (DMI) records timing pulses as a function of a wheel rotation, consequently allowing highly accurate, linear travelled distance, captured in real time.

Assuming the measurement of these above independent subsystems meet accuracy expectations, the most important feature of a high-speed GPS / INS system is the ability of its subsystems to collaborate with one another and export location data in a synchronized manner.

Road pavement condition monitoring vehicles, such as the ARAN (Automatic Road Analyzer), is primarily used for the collection and reporting of pavement surface distress data and roadside inventory. These vehicles however are readily equipped with DMIs and all the above required subsystems for the collection of roadway horizontal and vertical alignments. Many state road authorities in Canada and the United States utilize the location reference data collected using such pavement survey vehicles for the development of network level, horizontal and vertical curvature parameters. (5) (7)

GPS Systems

A Global Positioning System's (GPS) receiver and one or two operating frequency antennas are used to measure timing information provided by an array of satellites in the sky. This information can then be used to determine the vehicle's latitude, longitude and elevation coordinate data. When a GPS unit operates independently, a minimum of 4 viewable (line-of-sight) satellites are required in order to calculate the vehicle's position and heading according to a given referencing system.

When combined in a GPS / INS closed loop, RTK corrected system, location data from as little as one satellite can be utilized for correction of the inertial data. Collection frequency intervals need to be of sufficient longitudinal resolution to ensure that changes in a curves' radius can be depicted even when a survey vehicle is travelling at highway speeds. More accurate systems utilize a differential correction service, alike that of the service operated by Omnistar, whereby numerous fixed base stations are used for the calibration of inconsistent coordinates due to the environmental factors such as clock errors, atmospheric errors, orbital errors, multipath errors or receiver errors.

Inertial navigation system (INS)

The inertial (INS) part of the system provides the means of mitigating the real-world effects of GPS outage, signal interference and multipath through the provision of a continual stream of location data, recording continual changes in the forces (acceleration) and vehicle orientation that were experienced by the vehicle as it navigates the roadway. The 3-axis gyroscopes measure instantaneous roadway geometry characteristics such a roll, pitch and grade of the vehicle. The 3-axis accelerometers work hand in hand with the DMI and GPS receiver to collect vehicle movement patterns to determine the vehicle's change in direction and alignment. These inertial subsystems ensure that surveys can be successfully collected in a range of roadway environments that could otherwise not be accurately collected using a standalone GPS system. For high speed data collection, the operating frequency of the Inertial Navigation Unit (INU) can prove pivotal in reportable accuracy of a GPS / INS system. At a higher operating frequency of 200Hz, the INU can collect data at an interval of 14 cm when travelling at a speed of 100km/h.

GPS / INS SYSTEM ACCURACY ON CURVE RADIUS

In order to improve the accuracy of a location referencing, an INS is often used to provide continual position data from the movement of the vehicle and assist during times of satellite signal interference. The POS LV 420 system, designed and manufactured by Applanix, is used as an example of these types of INS. This tightly coupled system combines a GPS unit, 3-axis gyroscopes, inertial accelerometers and a distance measurement instrument. These units are considered in the industry to be amongst the more accurate data-position referencing systems available on the market for engineering and geographic information system (GIS) purposes. Errors related to the instantaneous collection (with a few exceptions such as timing and post processing errors) of location (longitude, latitude and elevation), roll, pitch and direction heading, for traffic speed survey vehicles can be attributed to this system.

Using this system in a best case scenario, whereby numerous and non-interfered line of sight signals to satellites exist, the best achievable accuracies using the POS LV 420 systems are shown in Table 1. The error, shown in meters and degrees in Table 1 and Table 2, is the root mean square error (RMS Error) which was calculated using Equation 1.

$$RMS_{Error} = \sqrt{(Mean\ Error)^2 + (Standard\ Deviation\ of\ Error)^2}$$

Equation 1: Root mean square error

GPS accuracies can also be improved after collection using information and adjustments to satellite positions based on fixed base stations. The data is post processed using other software tools and regularly updated information available from navigation services. The accuracies reported (Table 1) are based on good satellite coverage and may be higher under some real world running conditions.

Table 1: Highest accuracy of an ARAN without GPS signal interference (11)

	Accuracy - POS LV 420	
ITEM	**REAL TIME (IARTK) DATA**	**POST PROCESSED DATA**
X, Y Position (m)	0.035	0.020
Z (Elevation) Position (m)	0.050	0.050
Roll and Pitch (°)	0.015	0.015
True Heading (°)	0.020	0.020

To simulate a situation where satellite signal has been degraded or lost all together, Table 2 reports accuracies (RMS Error) that are representative of a collection where satellite signal is uninterrupted, then lost completely for 60 consecutive seconds, and then fully retrieved. This example, which is a measurement of the accuracy of the inertial components of the system, simulates a scenario such as travelling through a tunnel or driving along dense forest or sky-scrapper environments. These accuracies are reported by the manufacturer and are the best achievable for this scenario using the POSLV 420 system.

Table 2: Highest accuracy of an ARAN assuming a 60 second complete loss of GPS signal (11)

	ERROR - POS LV 420	
ITEM	**REAL TIME (IARTK) DATA**	**POST PROCESSED DATA**
X, Y Position (m)	0.340	0.120
Z (Elevation) Position (m)	0.270	0.100
Roll and Pitch (°)	0.020	0.020
True Heading (°)	0.030	0.020

These scenarios present the accuracies achievable for ideal and far from ideal scenarios. Using these accuracies it could be assumed that for the measurement of horizontal curvature based off latitude and longitude coordinate locations alone would be capable to determining (x, y) positions along a curve with an absolute accuracy of between 0.12m (POS LV 420 using post processed data) and 1.27m (POS LV 210 using IARTK real time data). Additionally if the heading direction data is utilized, accuracies in the development of horizontal curve measurements can be further improved.

To take into account the expected real world considerations that could result from the collection of horizontal curve data on a network level collection project, additional feedback was included. Such 'real world' considerations that may influence the degree of accuracy in reporting curve data may include:

- The unknown duration for which line-of-site signal between satellites and the GPS antenna is interrupted and hence the reported accuracy of inertial systems to navigate horizontal alignments alone; and
- The higher degree of error expected upon start-up of the POS-LV system in which time is required for the unit to learn its current location and effectively improve its accuracy (this was found to be aided by driving the vehicle through areas of clear sky).

The experience with the POS 420 units has been very positive on our large fleet of pavement, data collection vehicles (ARANs). From extensive experience of the units fitted to their collection vehicles, we are confident that the following accuracies can be obtained on a network level collection:

- For real time (IARTK) collected data an average, reportable error of less than 0.5m can be expected for two standard deviations (99.5%) of readings; and
- For post-processed data (using POSPac software) a 0.1m range in error can be expected for two standard deviations (99.5%) of readings.

The nature of a GPS / INS system is for the collection of GPS coordinates to perform corrections to the inertial system whenever possible (at 0.1 second intervals where possible). When GPS coordinate locations are not available to perform these corrections, the inertial system uses the translational and rotational motions of the vehicle to simulate horizontal alignments (coordinates) of the roadway. Without correctional data provided by the GPS system, errors accumulate with increasing time. Further the rate at which these errors accumulate is in part dependent on the path that the vehicle takes.

The extent by which these location errors in the latitude and longitude coordinates contribute to error in the prediction of curve length and radii is more difficult to predict. The consistency of error orientation along a horizontal curve (whether errors are skewed in one particular direction) has been found to be unbiased. Consequently this has implications on measuring horizontal curvature when GPS signal between the survey vehicle and satellites has been lost or degraded.

The higher accuracy of the DMI (Distance Measuring Instrument) contributes very little error in the calculation of road way chainage.

The primary sources that contribute to error for inertial based systems include (12):

- Accelerometers and gyroscopes instrumental errors such misalignment errors, biases, and drifts;
- The section inertial navigation model errors;
- Inertial position, velocity and alignment errors; and
- Other errors such as analog-to-digital quantization errors.

A function of one or more of these combined errors will accumulate with increasing collection time due to the time integration involved in the solutions of the nonlinear differential dynamic navigation equations. The use of post processing algorithms, such as curve fitting (see section below) is utilized to perform corrections to errors attributed to inaccuracies of the GPS / INS system. Further, through proper calibration and care of the equipment, many of these errors can be minimized.

CURVE FITTING ALGORITHM

Once the GPS trail has been measured, the location information needs to be converted into a series of curves to be evaluated. Post processing algorithms have been designed to sort, fit and manipulate the collected location (coordinate) data. For the curve fitting, the latitude and longitude coordinates are connected to form the representative lines and arcs to recreate road alignments as accurately as possible. In order to do this, curve fitting algorithms typically follow this set out procedure to best determine if an array of location coordinates belong to an arc of a set radius and length, or to a straight line.

Horizontal Curve Fitting Algorithm

To fit the data, an iterative process is used to evaluate all of the potential combinations of lines and curves to determine what best matches the data. The process looks at the data points in different combinations and uses an error tolerance to try and break up the data into the lines and arcs that will form the travelled path. A typical curve fitting algorithm is developed off the following simple procedure:

1. Do the collection of incoming data points (x, y coordinate) form a line?

Using a least squares method (minimizing error perpendicular to the line), a line of best fit is developed to determine whether the series of data points form a straight line with high statistical significance. This process is repeated until each point has minimized its x and y component errors to the chosen line of best fit.

2. Detect if the incoming points form an arc.

This is achieved by creating a circle of best fit that encompasses consecutive collection points, all of which must be within a known threshold distance, perpendicular from the instantaneous, tangential direction of the predicted circle. As soon as the next consecutive point is outside the allowable threshold distance from the circle of best fit, the previous point forms the end point of the arc. In order to define a circle that best fits the given number of points, two algebraic methods are employed:

- Newton Based Taubin method, followed by
- Gauss-Newton Algorithm.

The Newton Based Taubin method is first used to provide an initial estimate, followed by using the Gauss-Newton Algorithm to develop a more accurate representation to whether a number of points form an arc, using the following equation:

$$\sum (Distance(P_i, C) - r)^2$$

Equation 2: Algorithm for determining whether a point belongs to an arc (13)

Where P(i) is the set of measured points, C is the estimated circle centre, and r is the radius of the circle. To determine the transition between adjacent arcs, a maximum positional error is used. If the distance from each point to the circle is lower than an allowed input then bound then the circle arc from the first to the last point is reported, otherwise the points cannot form an arc.

3. Repeat the algorithm until the full input is parsed.

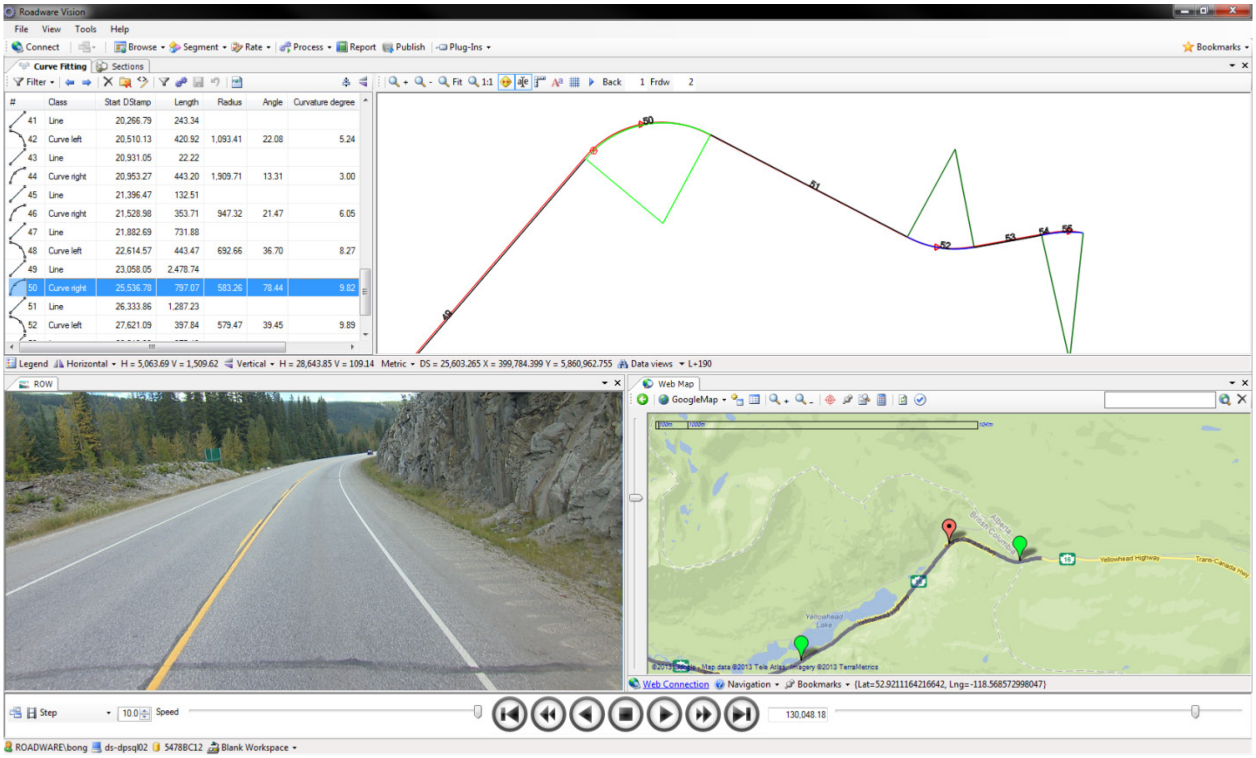

Figure 7 Horizontal curve fitting example using the Roadware Vision application

The error tolerances used in the analysis can have a very large effect on the results. For lower tolerances, longer curves are identified with a lower level of accuracy. If the tolerance is set tighter, larger curves are broken into many shorter curves. The effect is even higher on spiral and transition curves where the radius of the curve is expected to change along the curve. In order to perform sensitivity analysis of the algorithm and such determine the best fit for a given alignment, the following parameters can be defined by the user to reproduce a sequence of curves and lines that best suit their requirements.

- **Distance tolerance for line fitting:** Sets the upper limit for tolerable errors between the data point of interest and the line of best fit.
- **Distance tolerance for arc fitting**: Sets the upper tolerable limit for errors between the data point and the circle of best fit. If the data point is found to be outside of the tolerable error limit, the previous point along the defined circle will form the arc end point.
- **Minimum / maximum arc radii:** Controls the output of arcs by testing the radius to fit between the minimum and maximum allowable radii. If the radius is found to be outside this allowable range then the road is fitted by lines which respect their tolerances.
- **Minimum arc angle:** After an arc is detected its length is compared to the minimum arc angle parameter. To prevent an excessive number of very short angles being identified, if the length is found to be less than this parameter the arc is removed and added to the previous found best line is outputted instead.
- **Percent of maximum consecutive lines discrepancy:** When multiple consecutive lines are detected, a ratio is computed between the straight distance (start of the first

line to the end of the last line) and the sum of individual lines distance. If the ratio is within the percent set for the parameter and 100% then all the lines are merged together and reported as a straight line.

Vertical Curve Fitting Algorithm

The vertical curve technique is very similar to that of the horizontal curve. The technique has been simplified to a function of elevation and instead of using a circle to fit to the data, vertical parabolic functions are used to quickly identify both peaks and valleys. For detecting a best fit parabola which minimizes the statistical distance square error for N points, a linear system of equations is formed and solved (13). The algorithm operates by starting from a current point and attempts to add points to the current parabola until the maximum error distance (deviation) is greater than a specified bound (parameter). The algorithm then returns a list of best-fitted parabolas for the given points.

The three step process identified for the horizontal curve-fitting algorithm described above is followed and the many parameters are duplicated for vertical curves as well.

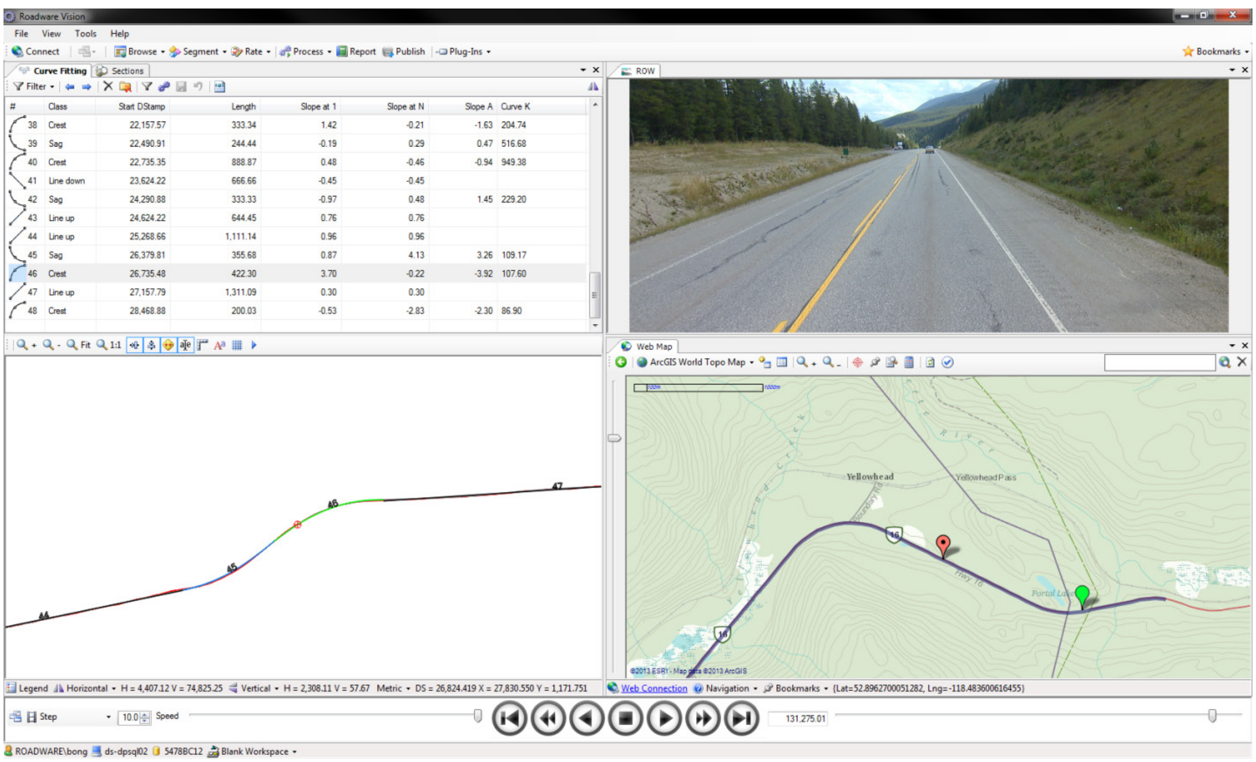

Figure 8 Vertical curve fitting example using the Roadware Vision application

Limitations of the Curve Fitting Algorithms

The simplicity of this algorithm allows for all parts of the road to be broken down into simple shapes that can be further analyzed. For horizontal curves, the circular shape is well understood and relates directly to the horizontal friction forces required to stay on the road at specified design speed. For vertical curves, the parabolic shape provides a simple shape to determine the location of peaks and valleys and can be quickly scanned to determine sight and stopping sight distances.

The process is computational effective and provides valuable information, but does have some limitations. Since the curves are being selected independently of each other, the path will not be perfectly smooth. Small, discontinuous differences in heading will exist between curves and tangent sections. This limitation means that curves are not always aesthetically pleasing. Depending on the need for the data, it is important to note that the discontinuities mean the data cannot be used directly as a profile for other analysis or modeling.

Also of note is that the data is limited to that collected by the vehicle. This means that the path to be matched is that of the vehicle doing the collection which can be affected by many other factors during collection. Some of these limitations can include:

- Vehicle wander within the lane;
- Lane changes due to obstructions;
- Changes in lane configuration.

These factors require that that the results be reviewed to ensure that the path driven is representative of the curve being analyzed.

THEORETICAL ANALYSIS OF THE INFLUENCE OF VEHICLE WANDER ON HORIZONTAL CURVE RADIUS

A theoretical analysis was undertaken to assess the influence that vehicle wander, particularly the driven path at curve entry, midpoint and exit can have on the calculation of horizontal radius for a series of curves. This analysis is based on mathematically generated curves and induced errors on the curve to determine how much affect changes to a perfect curve will affect measured radius. This is intended to serve as a guide to better understand the error tolerance expected from a survey vehicle on a real highway.

This analysis is based off typical wander that could occur within a given lane, and does not incorporate any influence from a vehicle changing lanes while navigating a curve or from the collection of curve alignments resulting from two alternate driven directions. Allowable vehicle wander from the centreline of a curve (Figure 9) was limited to 0.5m to either side of this lane's centreline. This matches the assumption used in the curve fit analysis as the maximum deviation from the path.

This analysis, based on simple curves (transition or spiral curves were not assessed as a part of this analysis), investigates the horizontal curve radius for the following two extremity scenarios (Figure 9):

- Scenario 1: On the approach to the curve the vehicle starts 0.5m to the inside of the lane's centreline, strays to 0.5m to the outside of the centreline at the curve lengths midpoint and finally returns to 0.5m to the inside of the curve at the curves end point. This curve scenario is shown in red in Figure 9.
- Scenario 2: On the approach to the curve the vehicle starts 0.5m to the outside of the centreline, strays to 0.5m to the inside of the centreline at the curve lengths midpoint and finally returns to 0.5m to the outside of the curve at the curves end point. The curve scenario is shown in blue in Figure 9.

For each of the two scenarios the influence of driver wander on curve radius was assessed for curves with arcs varying from 22.5° to 90° turns. The variation (or degree of error) between the radius of the curve along the centreline and the new radius according to the two scenarios can such be assessed. Shown in Figure 9, scenario 1 would represent the curve with the smaller radius while the scenario 2 would represent the curve with the largest radius.

This analysis was based off the following circular function formula:

$$R^2 = x^2 + y^2 \quad \text{(Curve centered at 0, 0)}$$

Equation 3: Circular function formula

$$R^2 = (x - A)^2 + (y - B)^2$$

Equation 4: Circular *function* formula for curve centered at (A, B)

Where:

R - Radius (m);
x - Horizontal component of the circular curve (m);
y - Vertical component of the circular curve (m);
A, B - Relocation of circular curve centre in the respective x and y directions (m).

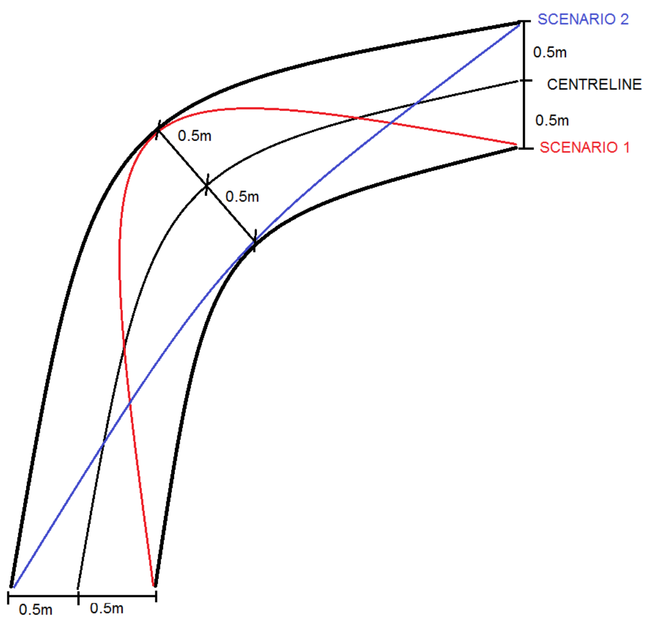

Figure 9: Basic illustration *of* 0.5m vehicle wander along a simple horizontal curve

The radius, R, was calculated at 10 equal degree intervals along the curve, increasing by 1.0m (3.3 feet) for scenario 1 between start point and mid-point of curve, and decreasing by 1.0m from midpoint to curve end. The opposite pattern is used to create scenario 2. Due to the fact that the two developed curves now consisted of multiple radii (similar to that of a transition curve), a single, representative radius was needed to compare against the centreline radius. A least squares error regression was used to determine the predicted arc for each degree interval, by interchanging variables A, B of Equation 4, and the summary radius.

The predicted error was calculated based on curve radii of between 10m (33 feet) and 1,500m (4,921 feet) for arc lengths of 22.5^0, 45^0 and 90^0. As expected, the influence of a 0.5m wander from the centreline would more significantly alter the radius of a shorter turn as compared to a longer turn. As an example, for a centreline curve radius of 250m (820 ft), vehicle wander according to scenario 1 would have an effective radius of 252.6m (829 ft) for a 90^0 turn, 260.5m (855 ft) for a 45^0 turn and 287.7m (944 ft) for a 22.5^0 turn. For the same 250m (820 ft) curve radius, vehicle wander according to scenario 2 would have an effective radius of 247.4m (812 ft) for a 90^0 turn, 238.6m (783 ft) for a 45^0 turn and 197.3m (647 ft) for a 22.5^0 turn.

The relationship between this influence on curve radius (shown as the percentage of variation between centreline and vehicle radii) and increasing centreline radius for 22.5^0, 45^0 and 90^0 degree turns is shown in Figure 10 and Figure 11, for scenario 1 and scenario 2 respectively.

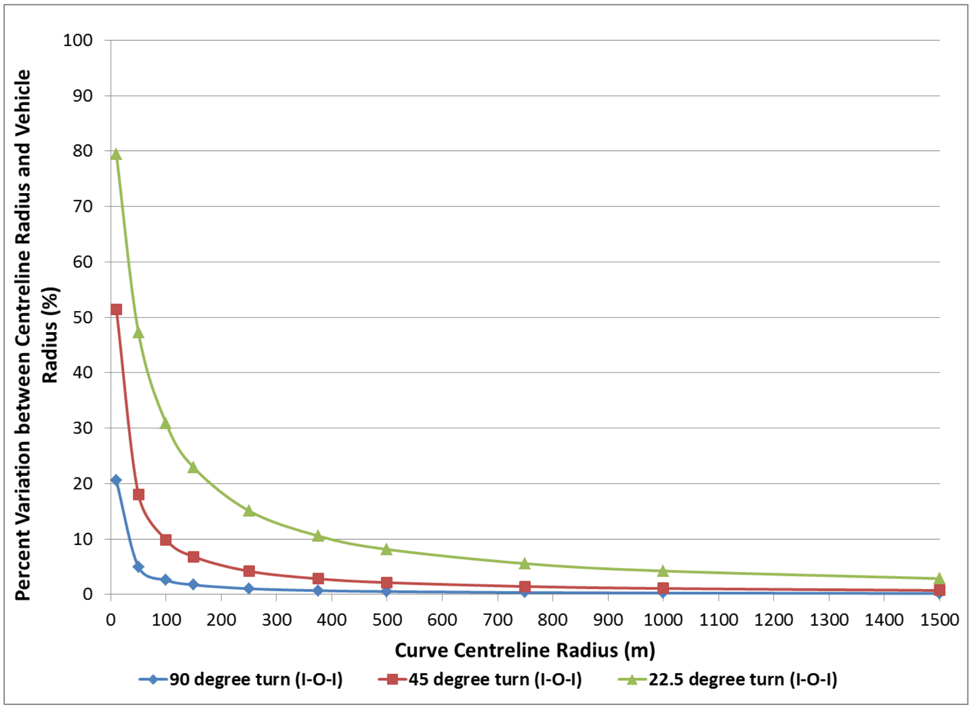

Figure 10: Percentage of variation between radius of lane centreline and radius of vehicle (scenario 1)

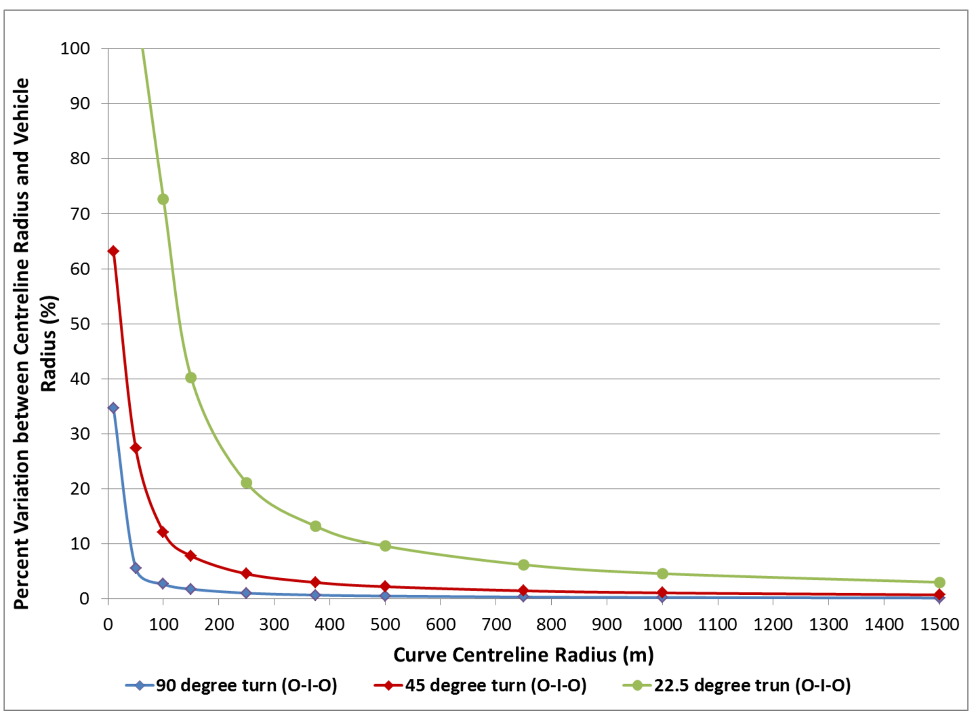

Figure 11: Percentage of variation between radius of lane centreline and radius of vehicle (scenario 2)

From this theoretical analysis the following conclusions could be drawn:

- Scenario 2, the larger radius of the two examples is more susceptible to error in the prediction of curve radius incorporating driver wander.
- Curves of low angles are more susceptible to error in the prediction of curve radius incorporating driver wander as seen in scenario 1 and 2.
- The errors associated in the prediction of curve radii incorporating this driver wander increases in an exponential manner as the centreline radius of the curve decreases relative to the acceptable error.

The decrease in equivalent radius from the road lane centreline to the vehicle driven path shown in scenario 1, presents a road safety implication. For the purpose of geometric design of horizontal alignment, the minimum acceptable radius (measured to the inside line of the inner most lane) is a product of the superelavation of the roadway, a side friction factor and design speed (discounting the stopping sight distance criteria) (8). Assuming the side friction factor and superelavation of the roadway remain constant, the curve radius and design speed remain closely, if not directly related.

For the design of short curves of small radii (250m or less), the difference between the design radius and the vehicle travelled radius can differ by 5% or more for an error level of 0.5m. While not a significant reduction in radius, for the assessment of curve radius adequacy for existing horizontal alignments (with set design speeds), this could make the difference between compliant and non-compliant radii for shorter curve lengths of lower deflection angles. Further, for the relationships presented in Figure 5, the influence that percent error in the prediction of curve radii can have on the subsequent change in vehicle crash frequency (5), error that is only minor in extent can contribute to the degrading safety of a given roadways alignment.

CONCLUSIONS

The ability to measure the geometric features of a road using traffic speed survey vehicles has many potential benefits. The ability to collect and process this information as a part of pavement condition surveys, which are regularly performed for most provincial transportation agencies, allows for the extraction of accurate location referencing data to be obtained time and cost effectively.

The accuracy of a survey vehicle's combined GPS / INS allow for a very effective measurement of the driven path (reproduction of latitude, longitude, elevation and heading) to be collected at traffic speed, and under a range of satellite interference conditions. The real world accuracy of an ARAN with combined GPS and INS system allows for a trail with a positional accuracy of under 0.5 m to be reported.

The curve-fitting algorithm discussed in this paper, used to process position data, and collected using a GPS / INS vehicle, has shown to be a robust and repeatable algorithm. It can consistently convert the horizontal path into a series of tangent sections and circular arcs. The vertical curve fit process converts the path into a series of tangent grades and parabolic peaks and valleys.

Selection of discussed curve fitting parameters when using the curve-fitting algorithm can greatly influence the number of curves detected and their associated length. If tolerances are high, curves may be split into more frequent smaller curve lengths. Depending on the nature of the sections being measured, it may be necessary to regularly adjust these parameters in order to optimize a curve fitting approach that best suits the roadway alignment.

Due to the nature of the collection of horizontal alignment data, factors such as vehicle wander within lanes, lane changes, and lane closures have the potential to affect the results. The level of error induced by these movements is very dependent on the arc radius and arc length. For shorter arc lengths, the potential curve radius error from vehicle wander (in excess of 5% for small radii curves) becomes more of concern as curve deflection decreases.

Consequently, and when considering the sensitivity of crash frequency based on the percent error in the prediction of curve radius (Figure 5), just care is recommended when applying design restrictions, such as minimum radius and design speed, for curves of shorter curve arcs.

RECOMMENDATIONS

Discrepancies between horizontal curve radii calculated from a vehicle navigating the roadway and that of as-built construction plans can differ by as much as 5% or more for smaller curvature angles. This presents a safety implication along such curve types, whereby crash frequencies are predicted to increase as the error in curve radius increases. It would such be recommended that further research, including field trials, be carried out to investigate the influence of driver behavior, such as vehicle wander and lane changes, has on the radius of a curve.

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