Development of Highway Alignment Information from Photolog Data

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The Wisconsin Department of Transportation operates an instrumented vehicle that collects both photolog and digitized geometric data on roadway bearing, grade, and cross slope. These data are recorded every 0.01 mile. The objective of the research was to develop the methodology and computer software necessary to transform the digitized roadway data into a highway alignment data base for use in inventory studies, deficiency analyses, and preliminary design studies. The software created locates horizontal curves and provides estimates of the radius, length, superelevation, and maximum recommended speed. A vertical profile can be plotted, and the location of segments with either stopping or passing sight distance restrictions due to horizontal and vertical alignment are identified. The software was tested and validated by using as-built plan and profile data for a case study highway.

The Wisconsin Department of Transportation (WisDOT) operates an instrumented vehicle equipped with a Techwest Photologging System (*1*) to collect both photolog and digitized geometric data for highways under its jurisdiction. This information (referred to in this paper as the datalog file and shown in Figure 1) is recorded at 0.01-mile intervals, or every 52.8 ft. The department's goal is to create a videodisk and computer software system for retrieving and displaying high-resolution photographic images concurrently with corresponding geometric data. This system would provide highway planners and engineers with a high-quality, accessible data base for conducting inventory studies, deficiency analyses, and preliminary design studies.

The objective of this research was to develop the methodology and computer software necessary to transform the digitized roadway data into a highway alignment data base, which was to include information on horizontal and vertical alignment as well as sight distance restrictions.

DATA BASE

When the driver of the instrumented vehicle arrives at a highway segment to be measured, he or she manually sets the highway name, county name, and beginning odometer reading. A plus or minus sign is specified for the odometer reading, according to the direction of travel. If one direction is listed as plus, the opposite direction will have a minus sign. Usually, a one-directional datalog file is created because the northbound and southbound runs will have different file names. This information is stored in the datalog file.

The bearing of the vehicle is automatically determined by a gyro compass. Percent grade is recorded by using an electrically powered gyro as a reference platform. Transverse slope is recorded by using the grade gyro with a sensor perpendicular to the grade sensor. This sensor indicates the total transverse slope of the road, plus any slope contributed by the vehicle due to static or dynamic loading. This bearing and slope information is recorded every 0.01 mile.

DEVELOPMENT OF VERTICAL ALIGNMENT

A two-step methodology was used to develop vertical alignment information from the datalog file. The first step involved adjustment of the original grade readings; the second involved calculation of the elevation of the highway at each record.

Because the raw data collected by the instrumented vehicle contained a substantial amount of noise, due largely to the bouncing motion of the vehicle, it was necessary to smooth these data before attempting to establish the elevation at each record along the highway section. The grade readings from the datalog file were plotted against the true grades, using several case study sites for which a current set of plan and profile drawings were available. Regression analysis was then performed to develop a set of adjustment models that would be able to eliminate much of the noise in the raw data. It was found that the errors were a function of whether the vehicle was operating on a positive or negative grade. The resulting regression models are

$$\overline{G} = 0.0744 + 0.847\,(+G) \tag{1}$$

$$\overline{G} = -\,0.151 + 0.980\,(-G) \tag{2}$$

where

$+G$ = positive grading reading,
$-G$ = negative grade reading, and
$\overline{G}$ = adjusted grade.

The R^2 for the models are 0.937 and 0.926, respectively.

The software uses the regression models to adjust the grade readings, after which the elevations at each successive record are calculated as

$$E(i) = E(i-1) - 52.8 \sin\,[\overline{G}(i)/100] \tag{3}$$

where $E(i)$ is the elevation at record i and $\overline{G}(i)$ is the adjusted grade at record i. A graphical plot of the highway profile may

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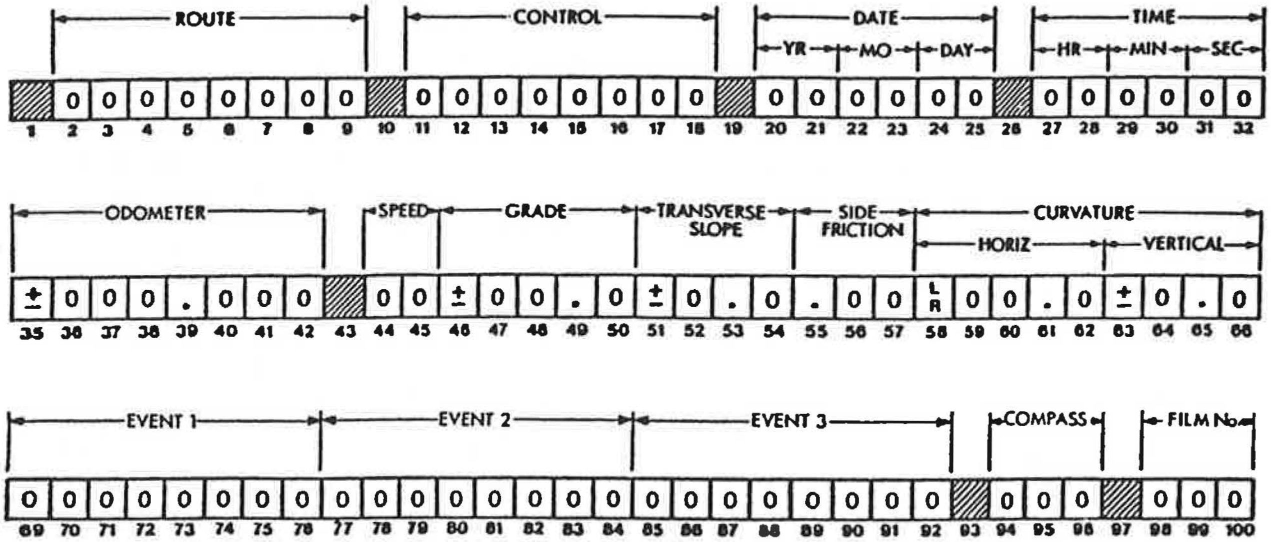

FIGURE 1 Format of the datalog file.

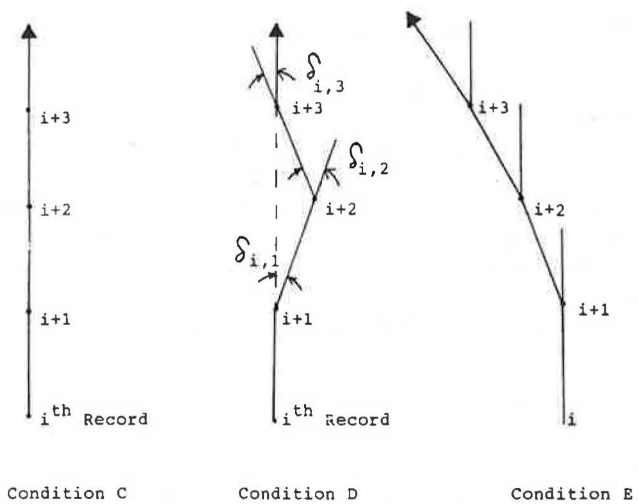

FIGURE 2 Horizontal alignment test conditions.

then be requested. The location of the points of curvature (PC) and tangency (PT) could not be successfully programmed because of the difficulty in separating the inherent remaining noise in the adjusted grades from the gradual grade changes associated with the beginning or end of a parabolic curve. Further research is underway to overcome this problem.

DEVELOPMENT OF HORIZONTAL ALIGNMENT

The algorithm developed to locate the points of curvature (PC) and tangency (PT) for a horizontal curve involves the following steps. The conditions tested in Steps 3 through 5 are illustrated in Figure 2.

1. The program reads the compass bearing at every record i and filters out inconsistent records by checking three consecutive compass bearings: C_i, C_{i+1}, and C_{i+2}. If $C_i = C_{i+2}$, then C_{i+1} is set equal to C_i, and the process is repeated for the next record.
2. The program calculates changes in compass bearings for each record between the current record i and record $i + 3$. These are then referenced with respect to the current record:

$$\delta_{i,1} = C_i - C_{i+1} \tag{4}$$

$$\delta_{i,2} = C_{i+1} - C_{i+2} \tag{5}$$

$$\delta_{i,3} = C_{i+2} - C_{i+3} \tag{6}$$

where C_i, C_{i+1}, C_{i+2}, C_{i+3} are compass bearings for records i, $i + 1$, $i + 2$, and $i + 3$, respectively, and i is the current record.

3. If $\delta_{i,1} * \delta_{i,2} < 0$, then record i is identified as being on a tangent. Select the next record, and return to Step 2. Otherwise, go to Step 4.
4. If $\delta_{i,1} = \delta_{i,2} = 0$, then it is assumed that the driver of the datalog vehicle has made a steering error on a tangent section. Select the next record and return to Step 2; otherwise go to Step 5.
5. If neither condition 3 nor condition 4 is satisfied, it is assumed that record $i + 1$ is within a curve. However, the program does not pick the PC until it encounters the PT of a curve. The program finds the PT first, and it counts the frequency of events, n, where the condition e was satisfied. The program then establishes the PC by subtracting n from the PT.
6. If $\delta_{i,3} = 0$, go to Step 7; otherwise select the next record and return to Step 2.
7. The PT is found at record $i + 3$. Subsequently, the program resets all flags associated with a curve by increasing the curve number. In addition, the highway name, county name, and direction of a curve are reported in this step.

Once the PC and PT for a horizontal curve are found, the program computes the following parameters. The calculation of radius of curvature accounts for the position of the center of gravity of the datalog vehicle that is assumed to be approximately 6 ft to the right of the highway centerline.

$$L = 5280(\mathrm{ODM}_{PT} - \mathrm{ODM}_{PC}) \quad (7)$$

$$R = [L/(C_{PT} - C_{PC})](180/\pi) + 6 \quad \text{right-hand curve}$$
$$R = [L/(C_{PT} - C_{PC})](180/\pi) + 6 \quad \text{left-hand curve} \quad (8)$$

$$D = 5730/R \quad (9)$$

where

L = length of curve (ft);
ODM_{PT}, ODM_{PC} = odometer readings at the PT and PC;
C_{PT}, C_{PC} = compass bearing at the PT and PC, respectively;
D = degree of curvature; and
R = radius (ft).

The superelevation of the curve, e, is obtained by taking the average of the transverse slope readings from the datalog file:

$$e = \frac{\mathrm{TS}}{(\mathrm{ODM}_{PT} - \mathrm{ODM}_{PC})100} \quad (10)$$

where ODM_{PC} and ODM_{PT} are odometer readings for the PC and PT, and TS is the sum of the transverse slope readings on a horizontal curve.

After these three parameters are calculated, the program determines the maximum recommended speed on the curve. The speed at which a driver will travel around a horizontal curve when not restrained by a vehicle ahead is dependent primarily on two factors: the driver's sense of safety as judged from the sight distance ahead and the comfort as judged by the centrifugal force. On a horizontal curve the centrifugal force tending to keep the vehicle in a straight path is opposed by the side frictional force developed at the area of contact between the tire and the roadway surface. Additionally, the speed may be influenced by roadside markings of the safe speed. Assuming that sight distance is adequate, the maximum recommended speed is governed by the radius of curvature, the superelevation, and the allowable coefficient of friction between the tires and pavement surface:

$$V = [15R(e + f)]^{0.5} \quad (11)$$

where

V = maximum recommended speed (mph),
e = superelevation, and
f = allowable side friction.

The program calculates the maximum recommended speed by using the computed values for radius and superelevation and a representative limiting side friction value of 0.12.

When two horizontal curves are within two records (105.6 ft) of each other, the two curves are merged. The program also identifies concurrent records for a highway segment. A concurrent record is created when the driver of the datalog vehicle encounters a highway segment that carries more than one route designation and for which a datalog file was created during a prior run. The program prints a report of the horizontal alignment data (Figure 3). Only the horizontal curve sections of a highway segment are listed in the horizontal alignment table; therefore, records not included in these curve sections are on tangent sections. A listing of any concurrent records is provided at the bottom of the horizontal alignment information table.

SIGHT DISTANCE EVALUATION

The availability of the horizontal alignment data permitted identification of those locations having either a stopping or passing sight distance restriction. For purposes of this research, the American Association of State Highway and Transportation Officials (AASHTO) definition (*2*) of stopping sight distance and both the Manual on Uniform Traffic Control Services (MUTCD) and the WisDOT definitions (*3*,*4*) of no-passing zone sight distance were used.

Minimum stopping sight distance (MSSD, in feet) is expressed as

$$\mathrm{MSSD} = 1.47\, Vt + V^2/[30/(f \pm G)] \quad (12)$$

where

V = design speed (mph),
t = perception-reaction time (2.5 sec),
f = coefficient of friction, and
G = grade (percent).

Driver's eye height and object height are assumed to be 3.5 and 0.5 ft, respectively.

= HORIZONTAL ALIGNMENT INFORMATION =

HIGHWAY	DIR	COUNTY	DATE	PC(Odm)	PT(Odm)	D	R(FT)	L(FT)	PI	e	DSN SPEED
STH017	N	LIN...01	84- 4-29	27.52	27.54	1.9R	3025.9	105.6	27.53	.036	84.
STH017	N	LIN...01	84- 4-29	27.73	27.75	1.9R	3025.9	105.6	27.74	.030	83.
STH017	N	LIN...01	84- 4-29	28.07	28.09	1.9R	3025.9	105.6	28.08	.017	79.
STH017	N	LIN...01	84- 4-29	28.35	28.37	1.9R	3025.9	105.6	28.36	.014	78.
STH017	N	LIN...01	84- 4-29	28.99	29.04	1.9L	3025.9	264.0	29.02	.041	86.
STH017	N	LIN...01	84- 4-29	29.06	29.18	2.1L	2793.1	633.6	29.12	.037	81.
STH017	N	LIN...01	84- 4-29	29.76	29.83	1.9L	3025.8	369.6	29.80	.019	79.
STH017	N	LIN...01	84- 4-29	29.85	29.87	1.9L	3025.9	105.6	29.86	.018	79.
STH017	N	LIN...01	84- 4-29	29.92	29.97	1.9L	3025.7	264.0	29.94	.012	77.
STH017	N	LIN...01	84- 4-29	29.99	30.03	1.9L	3025.9	211.2	30.01	.012	77.

FIGURE 3 Typical horizontal alignment information table.

The marking of a no-passing zone at a horizontal or vertical curve is based on the availability of a minimum passing sight distance at the prevailing off-peak 85th percentile speed of traffic (Table 1). The sight distance is evaluated using 3.5-ft eye and object heights.

Vertical Curve Sight Distance Deficiencies

The algorithms that were developed to locate stopping and passing sight distance deficiencies are virtually identical, except for the different sight distances and object heights used. The task was to locate the beginning and ending points of each zone in which there was either a stopping or passing sight distance restriction.

The algorithm used to locate vertical sight distance deficient segments involves the following steps:

1. Specify the design or 85th percentile speed and determine the appropriate sight distance requirement.
2. Calculate the elevation of Station (X + sight distance).
3. Calculate the elevation at each record between Station (X) and Station (X + sight distance).
4. Calculate the elevation of the sight line at each record between Station (X) and Station (X + sight distance).
5. If for any record between Station (X) and Station (X + sight distance) the sight line elevation is less than the profile elevation, then the sight distance is considered to be inadequate. When this condition takes place for the first time, the beginning point of a sight distance deficient segment is established.
6. Keep checking Step 4 until the available sight distance again becomes greater than the minimum value. At a record where this condition is satisfied, the ending point of a sight distance deficient segment is established.

The length of a sight distance deficient segment is calculated on the basis of the above beginning and ending points. The highway name and county name associated with a sight distance deficient segment are found by using the datalog records.

After the passing sight distance deficient segments are identified, a criterion is used to determine whether the distance between two successive segments is so short that the two segments should be connected. For this purpose, the MUTCD criterion of 400 ft is used.

The percentage of no-passing zones is then computed and displayed at the bottom of a no-passing zones summary table. Figure 4 illustrates the output reports.

TABLE 1 NO-PASSING ZONE CRITERIA

85th Percentile Speed (mph)	Minimum Passing Sight Distance (ft) MUTCD	Wis. MUTCD
30	500	
35		528
40	600	
45		686
50	800	
55		845
60	1,000	
65		1,108
70	1,200	

VERTICAL ALIGNMENT INFORMATION

PASSING SIGHT DISTANCE DEFICIENCY SEGMENTS

HIGHWAY	DIR	COUNTY	FROM(Odomtr)	TO(Odomtr)	L(FT)
STH017	N	LIN...01	27.56	27.74	950.4
STH017	N	LIN...01	27.99	28.06	369.6
STH017	N	LIN...01	28.46	28.61	792.0
STH017	N	LIN...01	28.99	29.06	369.6

% NO PASSING ZONE = 15.61(%)
TOTAL LENGTH DRIVEN = 15892.8(FT)

STOPPING SIGHT DISTANCE DEFICIENCY SEGMENT

HIGHWAY	DIR	COUNTY	FROM(Odomtr)	TO(Odomtr)	L(FT)
STH017	N	LIN...01	27.53	27.67	739.2
STH017	N	LIN...01	28.41	28.57	844.8

FIGURE 4 Typical vertical alignment information table.

Horizontal Curve Sight Distance Deficiencies

Sight distance at a horizontal curve is measured along the center of the lane of travel. The sight line is, however, a straight line that connects the driver's position and the end of the required sight distance. An algorithm was designed to check if an obstruction cuts off the sight line. The required middle ordinate, a distance from the sight line to the arc of the vehicle path, varies according to the driver's position and the radius of a horizontal curve. If the calculated middle ordinate, m, is less than a user-specified actual lateral clearance on a curve, then the current highway location is considered to have inadequate sight distance.

As described previously, the computer program calculates the radius of a curve with respect to the centerline of the highway. The user is asked to specify the available middle ordinate, m, with respect to the centerline of the highway. Therefore, to determine horizontal sight distance deficient segments, the program adjusts the radius and the middle ordinate to account for the position of the datalog vehicle in the center of the inside lane. Three sight distance evaluation procedures were designed to reflect the possible roadway geometry downstream from the driver's assumed position: tangent-to-curve, curve-to-curve, and tangent-to-tangent.

The tangent-to-curve situation involves a driver on a tangent section in advance of a curve and the end of the sight line on the curve section. This condition is illustrated in Figure 5. To determine a required m, the program performs a series of computations for a side angle ϕ. Also, two simultaneous equations are solved to find lengths of line segments $\overline{A \cdot D_1}$ and $A \cdot D_2$. Once these values are determined, the program calculates m to the center of the vehicle path as follows:

$$\theta = \frac{SD - \overline{A \cdot PC}}{R'} \quad \text{(radians)} \tag{13}$$

$$R' \cos \alpha = R' - \overline{A \cdot D_1} \sin \phi \tag{14}$$

$$\cos \alpha = 1 - (\overline{A \cdot D_1}/R') \sin \phi \tag{15}$$

hence,

$$\alpha = \cos^{-1} [1 - (A \cdot D_1/R') \cdot \sin \phi] \tag{16}$$

$$\delta = \alpha + \theta \tag{17}$$

$$m' = R'[1 - \cos (\delta/2)] \tag{18}$$

and

$$\begin{aligned} R &= R - 6 \quad \text{right-hand curve} \\ R' &= R + 6 \quad \text{left-hand curve} \end{aligned} \tag{19}$$

When both the driver and the end of the sight line fall within a curve section as illustrated in Figure 6, the middle ordinate, m', can be obtained using the following expression:

$$m' = R'[1 - \cos \theta/2] \tag{20}$$

To determine m' under the condition where both the driver and the end of the sight line are on two different tangent sections separated by a horizontal curve, it is necessary to calculate the X and Y positions shown in Figure 7. The length of a long chord that connects X and Y depends on the side angle ϕ. The procedure used to determine the middle ordinate

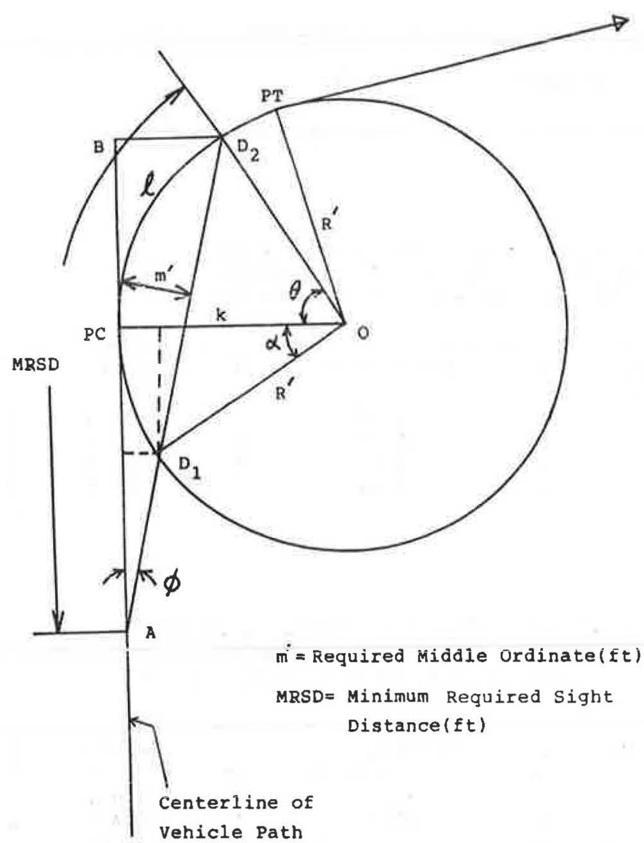

FIGURE 5 Tangent-to-curve sight distance situation.

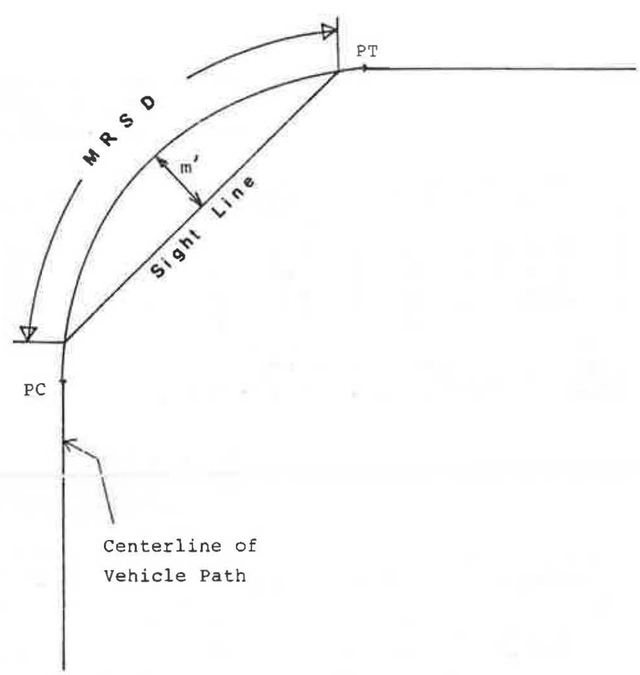

FIGURE 6 Curve-to-curve sight distance situation.

when the driver and the end of sight line are on different tangent sections is as follows:

1. Calculate the central angle of the horizontal curve:

$$\theta = l/r' \quad \text{(radians)} \tag{21}$$

$$x = R' \sin\theta \tag{22}$$

$$y = R'(1 - \cos\theta) \tag{23}$$

2. Calculate the x and y components for the straight line $\overline{PT \cdot B}$:

$$a = \overline{PT \cdot B} \sin\theta \tag{24}$$

$$b = \overline{PT \cdot B} \cos\theta \tag{25}$$

3. Determine the angle ϕ:

$$\overline{DB} = a + y \tag{26}$$

$$\phi = \tan^{-1}\left[\frac{\overline{DB}}{\overline{A \cdot PC} + \overline{D \cdot PC}}\right] \tag{27}$$

4. Calculate the angle α:

$$\alpha = \cos^{-1}[1 - (\overline{A \cdot D_1}/R') \sin\phi] \tag{28}$$

5. Calculate the angle γ. This requires the same procedure shown in Steps 1 through 4, except that the driver is assumed to be at point B, as shown in Figure 8:

$$\eta = (90 - \phi) - (90 - \beta) = \beta - \phi \tag{29}$$

$$\overline{B \cdot D_1} = \frac{(2\,\overline{B \cdot PT} \cos\eta + 2\,R' \sin\eta) + \sqrt{Z}}{2} \tag{30}$$

$$\overline{B \cdot D_2} = \frac{(2\,\overline{B \cdot PT} \cos\eta + 2\,R' \sin\eta) - \sqrt{Z}}{2} \tag{31}$$

where

$$Z = (2\,\overline{B \cdot PT} \cos\eta + 2\,R' \sin\eta)^2 - 4\,\overline{B \cdot PT}^2 \tag{32}$$

Hence,

$$\overline{B \cdot D_2} \sin\eta = R'(1 - \cos\gamma) \tag{33}$$

$$\gamma = \cos^{-1}\left[1 - \frac{\overline{B \cdot D_2} \sin\eta}{R'}\right] \tag{34}$$

6. Compute the required middle ordinate, m':

$$\delta - \theta + \alpha + \gamma \tag{35}$$

$$m' = R'(1 - \cos\delta)/2 \tag{36}$$

$$\begin{aligned} m &= m' + 6 \quad \text{right-hand curve} \\ m &= m - 6 \quad \text{left-hand curve} \end{aligned} \tag{37}$$

A majority of stopping or passing sight distance deficient segments can be located using these three situations. How-

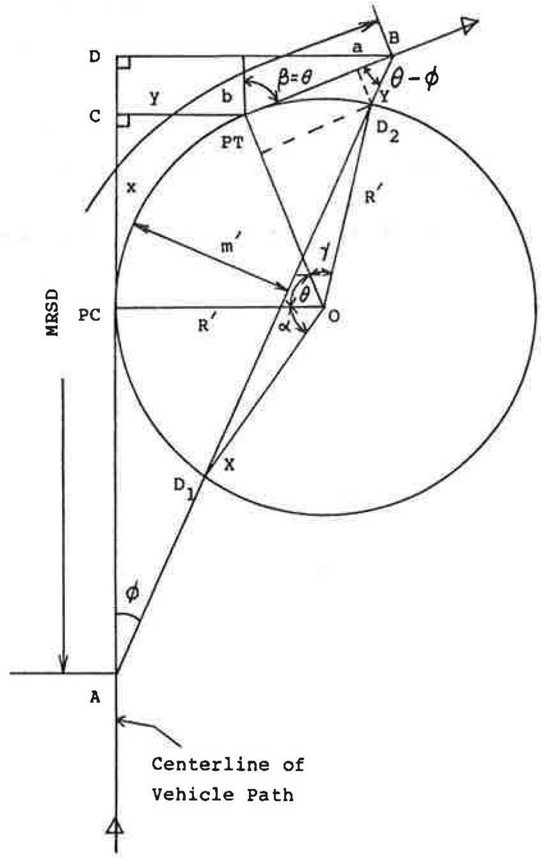

FIGURE 7 Tangent-to-tangent sight distance situation.

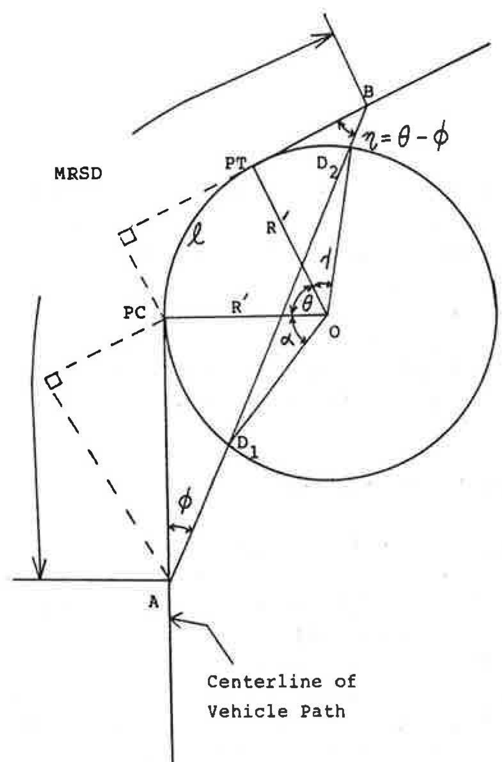

FIGURE 8 Diagram for angle γ.

- HORIZONTAL PASSING SIGHT DEFICIENCY SEGMENT -

HIGHWAY	DIR	COUNTY	FROM(Odmtr)	TO(Odmtr)	L(FT)
STH017	N	LIN...01	28.93	29.06	686.4
STH017	N	LIN...01	29.69	29.92	1214.4

FIGURE 9 Typical horizontal passing distance sight deficiency information.

TABLE 2 COMPARISON HORIZONTAL CURVE DATA

	Manual						Computer Program					
Curve #	PC (odm)	PT (odm)	D (°)	e	R (ft)	L (ft)	PC (odm)	PT (odm)	D (°)	e	R (ft)	L (ft)
1	27.46	28.48	1	.03	5730	5383	27.52	27.54	2	.04	3026	106
							27.73	27.75	2	.03	3026	106
							28.07	28.09	2	.02	3026	106
							28.35	28.37	2	.01	3026	106
2	28.97	29.19	2	.04	2865	1138	28.99	29.04	2	.04	3026	264
							29.06	29.18	2	.04	3026	634
3	29.72	30.09	1.5	.04	3820	1915	29.86	29.83	2	.02	3026	370
							29.85	29.87	2	.02	3026	106
							29.92	29.97	2	.01	3026	264
							29.99	30.03	2	.01	3026	211

ever, when two or more horizontal curves are separated within the required sight distance, the computer program may not produce reasonable results. When two successive horizontal passing sight distance deficient segments are separated by a tangent less than the 400-ft MUTCD criterion, they are combined to form a single no-passing zone. Finally, the program generates a summary of the horizontal passing sight distance deficient segments as illustrated in Figure 9.

SOFTWARE VALIDATION

The computer program was applied to a case study highway section to verify whether the software could accomplish its intended functions. The computer-generated information was compared with manual solutions developed near the as-built plan and profile drawings for the case study highway.

A comparison of the horizontal curve data is provided in Table 2. The relatively long curves were divided into several shorter curves by the computer program. This is probably due to the inherent noise in the data and the fact that such noise would have a more noticeable effect on low-degree curves. A comparison of the sight distance deficient segments is presented in Tables 3–5. When the computer-generated data were visually compared with photolog images, a very close correspondence was immediately apparent with respect to the beginning and ending points of horizontal and vertical curves, as well as no-passing zones.

CONCLUSIONS

Overall, the evaluation of the software indicated that it was possible to develop reasonably accurate highway alignment and sight distance data from the photolog system used by the Wisconsin Department of Transportation. The data are of sufficient accuracy to be used in an inventory data base or geographic information system and for deficiency analysis and preliminary project development. The system has the further advantage of eliminating the need for an existing set of plan and profile drawings. It is only necessary to operate the instrumented vehicle over the highway of interest and then to process the data using the software package.

TABLE 3 COMPARISON OF STOPPING SIGHT DISTANCE DEFICIENT SEGMENTS

	Manual			Computer Program			Difference		
Zone No.	From (odm)	To (odm)	*L* (ft)	From (odm)	To (odm)	*L* (ft)	From (odm)	To (odm)	*L* (ft)
1	27.57	27.75	950	27.53	27.67	739	−0.04	−0.08	−211
2	28.48	28.62	739	28.41	28.57	845	−0.07	−0.05	+106

TABLE 4 COMPARISON OF NO-PASSING ZONES AT VERTICAL CURVES

	Manual			Computer Program			Difference		
Zone No.	From (odm)	To (odm)	*L* (ft)	From (odm)	To (odm)	*L* (ft)	From (odm)	To (odm)	*L* (ft)
1	27.57	27.75	950	27.56	27.74	950	−0.01	−0.01	0
2	27.95	28.06	581	27.99	28.06	370	+0.04	0.00	−221
3	28.43	28.60	898	28.46	28.61	792	+0.03	+0.01	−106
4	28.97	29.05	422	28.99	29.06	370	+0.02	+0.01	−52

TABLE 5 COMPARISON OF NO-PASSING ZONES AT HORIZONTAL CURVES

	Manual			Computer Program			Difference		
Zone No.	From (odm)	To (odm)	*L* (ft)	From (odm)	To (odm)	*L* (ft)	From (odm)	To (odm)	*L* (ft)
1	28.89	29.10	1,108	28.91	29.08	898	+0.02	−0.02	−210
2	29.62	29.98	1,901	29.67	29.94	1,426	+0.05	−0.04	−475

REFERENCES

1. *Techwest Photologging System Operating Manual*. Techwest Enterprises Ltd., Vancouver, B.C., Canada, July 1984.
2. *A Policy of Geometric Design of Highways and Streets*. AASHTO, Washington, D.C., 1984.
3. *Manual of Uniform Traffic Control Devices*. FHWA, U.S. Department of Transportation, 1978.
4. *Wisconsin Manual on Traffic Control Devices*. Wisconsin Department of Transportation, Madison, 1984.

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