Surveying for Highway Alignment and Grade with Gyroscopic Equipment

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THIS report deals with a method of surveying for highway alignment and grades by using a gyroscopically equipped vehicle and describes a station-wagon in which two gyroscopes and auxiliary equipment necessary to run them have been installed. This auxiliary equipment includes a 750-watt generator, converter, voltage regulator, and inclinometer tubes.

One of the gyros is horizontally mounted and gives readings of azimuth and is continually controlled by or oriented to the earth's magnetic field for a reference base. The other gyro is vertically mounted which gives readings of grade and of superelevation.

The vehicle is operated at varying rates of speed depending on the degree of severity of the grade or alignment characteristics of the road traversed. A speed of 5 to 10 mph. is normal in most types of terrain.

Notes are taken which are subsequently reduced or calculated by IBM machine methods. Tabulations are furnished which give information in coordinates that enable the draftsman to readily plot the alignment features of the road. Grades are calculated and the elevations of recorded points are listed in feet or in any other unit desired. In addition to the coordinate points for alignment plots and the grade elevations, the IBM phase includes the determination of other detail such as radii of curves, central angle of curves and safe driving speeds.

Accuracies within 1 percent can be generally achieved in the matter of closures of traverses calculated by this method and errors in grade determination can be kept below ½ percent of grade. The method makes a provision for correcting grade and alignment closures by using a correction factor applied to the legs of the traverses run.

● A GOOD deal of experimentation and research has been carried on by the California Highway Planning Survey section of the Department of Public Works in conjunction with the Sperry Gyroscope Company of San Francisco to develop an instrument and technique that would measure and calculate data concerning alignment and grades on existing roads accurately and rapidly.

The need for such an instrument was occasioned by a request in 1947 by the Bureau of Public Roads that the department coöperate in testing a sight distance and curvature manual proposed by them. This manual proposed among other things that curve radii and degree of central angle data be furnished. The manual also proposed that data be collected to show length and percent of grade for the various grades.

Such an instrument and an operational technique have been devised that seen to have some promise in the field of rapid surveying.

The instrument is, in brief, a station wagon equipped with an odometer reading to the thousandth mile and two gyroscopes, one horizontally and one vertically installed that make possible the measurement of azimuths to the nearest degree and the measurement of grades and superelevations to the nearest percent.

The odometer works from a junction off the regular speedometer connection and has the desirable qualities of a reset, preset, and a backup-registering dial. It was devised and installed by Roy DeMartini Speedometer Sales and Service Company of Sacramento.

The horizontal gyroscope or the "gyrosyn" as it is termed in the trade, is so devised that it indicates azimuth to the nearest degree. It has a declination adjustment so that for a given locality it can be set to register true azimuths. A flux-valve mechanism keeps it from precessing from the true reading by causing magnetic lines of force to be applied against the proper gimbal of the gyro thereby continually "slaving" or bringing the gyro axis back to its relationship to the earth's magnetic field.

finely adjusted volt meters when the car body deviates from the horizontal plane. The amount of the deviation is measured in percent of grade and superelevation.

These two gyroscopes were installed by the Sperry Gyroscope Company of San Francisco, under the supervision of the Aeronautical Service Department of that company.

CALIFORNIA STATEWIDE HIGHWAY PLANNING SURVEY
GRADE AND ALIGNMENT SURVEY

CHPS RA III — SHEET 1 OF 8

ROAD DESCRIPTION Hum I K — CHIEF MCW — RECORDER RJM — TIME OF BEGINNING 1300 — DATE 23 May 51

NOTES	SEQUENCE CODE	BEGINNING ODOMETER	ENDING ODOMETER	GRADE	ALIGN CODE	AZIMUTH	CENTRAL ANGLE	SUPER ELEVATION
TRAVERSE NO 34	1							
NORTH ON HUM I K	2							
TIME 1300 23 MAY 51	3							
MCW MARTIN	4							
COOL CLOUDY	5							
ALIGNMENT TRUE	6							
BEGIN SEC HUM I K	7							
AT ODOMETER 19983	8							
OF TRAVERSE NO 33	9	00.000			LL	96		
		.000		0	CL			6L
		.060			T	89		
ORICK		.618		-1				
HWY MTCE STA ON RT		.640						
		.665			CL			6L
		.790			T	40		
		.885			CL			2L
		.925		+2				
BR 4 28 REDWOOD CR	1	.992						
USCGS BM J74	2							
ELEV 33 FT	3							
BEGIN TRUSS		1.024			T	05		
END TRUSS		1.070						
		1.075		-6	CR			3R
END BR		1.115						
		1.157		-1	T	25		
		1.240		0				
		1.630		+2	CR			2R
		1.810			T	38		

CR=Curve Right, CL=Curve Left, T=Tangent, TR=Change of Tangent Right, TL=Change of Tangent Left, RL=Point of Reverse Rt to Lt, LR=Point of Reverse Lt to Rt, RR=Point of Compound Rt to Rt, LL=Point of Compound Lt to Lt = Alignment Code

(When Super is 0 Designate by R for IBM Setting Procedure)

Figure 1. Field sheet for recording grade and alignment survey notes.

The vertical gyroscope is an adaptation of that used in the automatic landing control mechanism of aircraft, more particularly described as the A-12 Precision Gyropilot. The phenomenon of precession in this gryo is controlled by two level bubbles mounted parallel to each of the two gimbals of the gyro. Through a system of induced voltages, current is caused to be circuited through two

A combination of these three instruments, the odometer, the gyrosyn, and the vertical gyroscope make possible the measurement of: (1) distances to the nearest $\frac{1}{1000}$ mi., (2) azimuths to the nearest degree, and (3) grades and superelevations to the nearest percent.

Supplementary installations in the vehicle consist of: (1) a 110-volt, 750-watt generator to furnish the electrical current necessary to run the gyros, (2) a converter to change the cycle of the electric current from 60 to 400, (3) a voltage regulator to guarantee a steady flow of current to the registering dials, (4) two inclinometer tubes to make initial settings of the vertical gyro and to make possible quick intermediate checks at frequent stops, and (5) an aiming device installed on the front bumper to aid in setting the car in the correct position for an azimuth or generalized grade reading.

TRAVERSE NUMBER	REMARKS	ODOMETER MILES	ALIGNMENT CODES	CURVE DATA Δ DEG.	RADIUS FEET	% SUPER R—RT L—LT	SAFE DRIVING SPEED M.P.H.	LENGTH MILES ℄	TANGENT OR CHORD	AZIMUTH TANGENT OR CHORD NORTH=0	COORDINATES MILES Y NORTH	X EAST	GRADE DATA (CR—NEGATIVE) RATE %	ELEVATION FEET
34	TRAVERSE NO 34 NORTH ON HUM 1 K TIME 1300 23 MAY 51										89081	80775		7362
	MCW MARTIN COOL CLOUDY ALIGNMENT TRUE													
	BEGIN SEC HUM 1 K AT ODO 19983 OF TRAVERSE NO 33													
			LL CL	7	2598	6L	92	060	060	960 925	89078	80835		7362
		60	T					558	558	890	89088	81393		7362
	ORICK	618 618	T					022	022	890	89088	81415	1CR	7350
	MTCE STA RT	640 640	T					025	025	890	89088	81440	1CR	7337
		665	CL	49	771	6L	50	125	121	645	89140	81549	1CR	7271
		790	T					095	095	400	89213	81610	1CR	7221
		885	CL	10	1209	2L	57	040	040	350	89246	81633	1CR	7200
		925 925	LL CL	17	1193	2L	57	067	067	300 215	89308	81658	1CR 2	7271
	BR 4 28 REDWOOD CR USC AND GS BM J74 ELEV 33 FT	992 992 992												
		992 992	LL CL	8	1209	2L	57	032	032	130 90	89340	81663	2 2	7305
	BEGIN TRUSS	1024 1024	T					046	046	50	89386	81667	2	7354

T—TANGENT
TR—CHANGE OF TANGENT RIGHT
TL— " " " LEFT
© SC-28478

CR—CURVE RT.
CL—CURVE LT.

RL—POINT OF REVERSE—RIGHT CURVE TO LEFT CURVE
LR— " " " LEFT " " RIGHT "

RR—POINT OF COMPOUND—RIGHT CURVE TO RIGHT CURVE
LL— " " " LEFT " " LEFT "

GYROSCOPIC EQUIPMENT-ALIGNMENT AND GRADE SURVEY

Figure 2. IBM tabulation showing recorded and calculated data as prepared from gyroscopic grade and alignment survey notes.

In the operation of the vehicle, recordings are taken that indicate: (1) the odometer location of the beginnings and endings of all curves and tangent sections, (2) the azimuth reading of each tangent and at points of compounding or reversing of curves, (3) the superelevation of each curve encountered, (4) the odometer location of the estimated points of intersection of extended grades, (5) the percent of grade between those points, and (6) such notes as may be judged necessary for the use of the draftsman in delineating the final line traversed.

These notes are given to the planning survey's IBM section where they are processed mechanically and tabulations made that show, in addition to the recorded data, the following: (1) azimuth of the chord of the curve in degrees and half degrees; (2) central angle of curves in degrees; (3) intervening distances, i.e., lengths of tangents or curves in $\frac{1}{1000}$ mi.; (4) lengths of chords of curves in $\frac{1}{1000}$ mi.; (5) radii of curves in feet; (6) safe driving speeds on curves in miles per hour; (7) progressive departures or X-coördinate values (eastings or westings) in $\frac{1}{1000}$ mi.; (8) progressive latitudes or Y coördinate values (northings or southings) in $\frac{1}{1000}$ mi.; (9) grade profile or elevations in tenths of feet.

The data above are then plotted on 10-by-10 cross-section paper at a scale of usually 10 in. equals 1 mi. and the result is a plan and profile of the traversed road limited only to the degree of accuracy the fundamental instruments are designed to give.

Experience gained in the operation of this vehicle over about 2,800 miles of roads indicates that: (1) accuracies of 0.2 percent can be reliably expected in the odometer distances taken; (2) accuracies of from 0.5 percent to 0.9 percent may be reliably expected on the closure of traverses calculated (by the application of a factor in the IBM processes the error of closure can be eliminated); (3) grades can be reliably estimated to within one half of 1 percent; (4) the field operation phase can be done at a rate of about 5 mph; (5) the combined costs of operating the equipment in the field and of processing the field notes mechanically are well under $10 per mile of road traversed; and (6) the time taken to plot the IBM tabulations and to trace to a reproducible copy, varies a good deal depending on the topography; early figures indicate that a mile can be plotted and tracings made in about 3 hr.

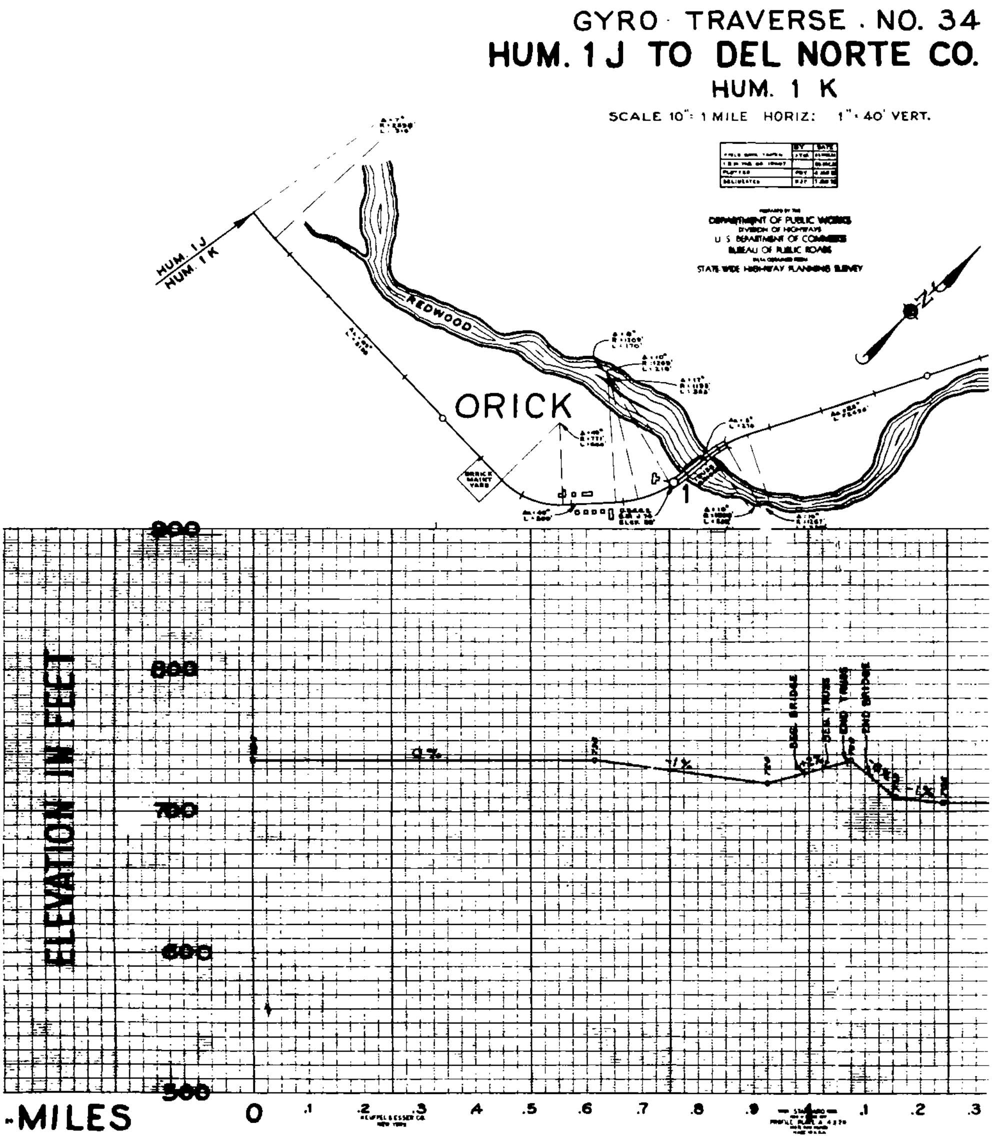
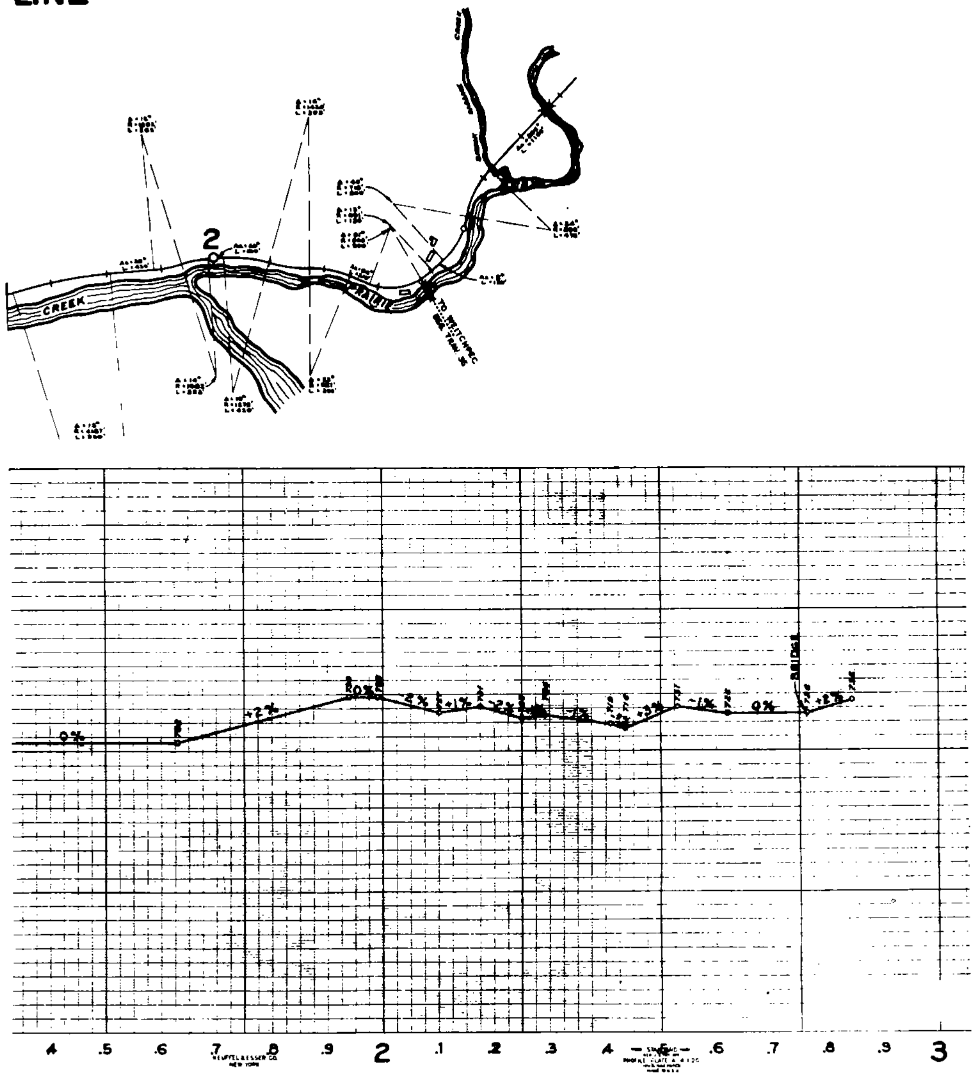


Figure 3. Plan and profile of a portion of traverse

The accuracy of the results of the gyro

traverse indicates that it compares favorably with the accuracies that might be expected of the more formal method of stadia traverse. An experimental project comprising 406 mi. processing, the larger the project the greater the speed that can be attained on a per mile basis as this processing lends itself to handling of mass data.

LINE



plotted from IBM tabulation data (see Fig. 2).

of gyro traversing conducted in San Bernardino County showed that data could be taken in the field, delivered to the IBM section for processing and a usable plot prepared within a period of four days. In regard to the IBM

Uses of this technique have so far been confined to the preparation of a plan and profile plot of such state highways that have never been formally surveyed; to the establishing of a key net of roads within a county which forms the basic net in road inventory procedures; and to furnish quick statistical data concerning alignment and grades on certain routes that can be obtained at much less expense and time than that required to review the existing plans.

It is anticipated that new uses will develop as the existence of the vehicle and the technique is made known on a broader basis. Up to the present, its operation has been confined to the planning survey section necessarily in order to establish an operational procedure,

Figure 4. Gyroscopic equipment in traveling position (top) and in operating position (bottom).

to test its accuracy and determine basic costs, and, all in all, to determine the practicality of the instrument and its attendent technique.

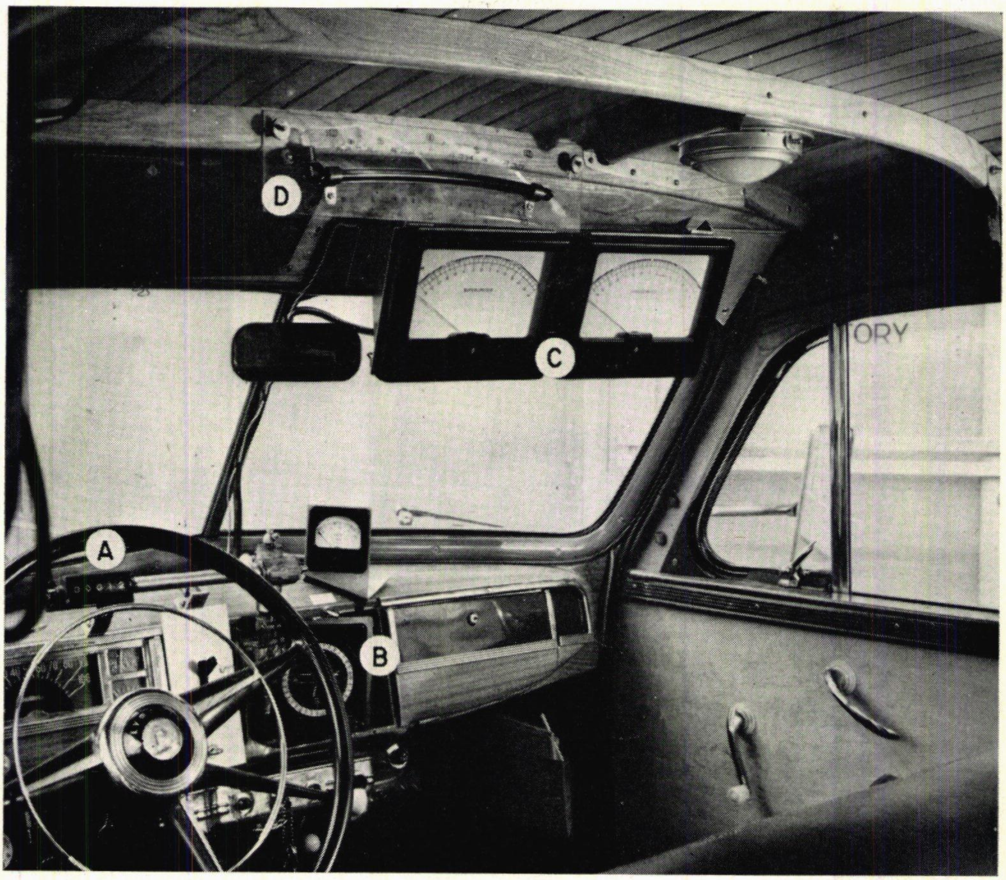


Figure 5. Operating instruments: A, odometer; B, horizontal gyroscope (Gyrosyn); C, superelevation and grade dials; and D, inclinometer tube.

DESCRIPTION OF BASIC INSTRUMENTS

Odometer

The odometer designed for and installed in the gyroscopic-equipment vehicle is merely a revolution counter turned by a cable off a junction with the regular speedometer cable. It is geared so that it registers each time the car goes through 5.28 ft. or 0.001 mi. of distance. It has a five digit registering dial hence it can register a distance up to 99.999 mi. It can be manually set to any predetermined figure as well as reset to zero. It also is reversing, that is, it will subtract when the car is backed up. This is useful, for cases occur where a mileage reading is left out or a position is overrun and when discovered merely backing up will establish it.

The fact that the odometer effectively works off the rear wheels means that its accuracy is dependent upon tire pressure. In this regard a test was designed to determine the effect of changing pressures on recorded distances. The Yolo Causeway was selected as a place to make such a test as it is a level and straight section for its complete length of 3.132 mi. This section was traversed 18 times at a rate of 20 mph. and at varying tire pressures. The following results were recorded.

Table 1 indicates that within the range of tire pressures from 27.5 to 40 lb. roughly 1 lb. of tire pressure change causes a change in the measured distance of 1 mi. by 0.001. This change seems to decrease for higher pressures and increase for the pressures lower than this range.

In addition to the effect of tire pressure the table indicates that operating temperature affects distances recorded. In this regard attention is directed to the two measured readings taken at 35 lb. pressure. One was taken in the morning when temperatures were cool and the other was taken in midafternoon when the temperature was at about a peak for the day. The difference of 0.014 mi. between these readings indicates that a degree rise in temperature affects the recorded distance nearly as much as a pound change of pressure.

Tire slippage has a very decided effect on recorded distances as was demonstrated on Traverse 37. The distance up a grade to a triangulation station known as Schoolhouse Peak was recorded as 0.468 mi. The return distance down grade was found to be 0.452 mi. The grade was severe enough that the vehicle had to be blocked and several spurts made to negotiate the top. It might be assumed that the tires slipped half the difference of 0.016 mi. or about 40 ft. on the way up in acceleration and 40 ft. in braking on the way down. Another instance of this phenomenon was in Traverses 57 and 58 the road to the top of Mt. Pierce, the Humboldt and Meridian Base. This road was generally on a severe up grade. Comparable distances recorded up and down were 4.976 and 4.850 mi. respectively. This difference of 0.126 mi. in the most part reflects this tire slippage factor.

When operating on normal terrain and comparing to established survey distances, it was found that accuracies of horizontal distance could be kept around 0.2 percent. Greater accuracies could be achieved in all likelihood by using a fifth wheel, where the tire pressure, operating temperature, and particularly slippage effects would be minimized. The inconvenience of attending such a device was considered to outweigh the advantages of the additional accuracy likely to be attained.

The odometer used was designed and installed by the Roy DeMartini Speedometer Sales and Service Company of Sacramento, and it has developed no problems of maintenance in the 2,870 mi. of road traversed.

TABLE 1
GYROSCOPIC EQUIPMENT VEHICLE
Effect of Tire Pressure on Odometer Lengths
Test Section—Yolo Causeway—3.132 Miles

Tire Pressure	Time of Day	Recorded Length		Difference Between Successive Runs		Error per Mile for Each Pound Difference in Tire Pressure
		Westerly	Easterly	Pressure	Average Recorded Length	
lb.	*hr.*	*mi.*	*mi.*	*lb.*		
42.5	13:30	3.123	3.121			
				2.5	0.004	0.0004
40.0	14:15	3.126	3.126			
				2.5	.007	.0008
37.5	15:00	3.133	3.133			
				2.5	.007	.0008
35.0	15:45	3.140	3.140			
				0	.014	
35.0	08:30	3.154	3.154			
				2.5	.006	.0008
32.5	09:15	3.161	3.159			
				2.5	.009	.0012
30.0	10:00	3.170	3.168			
				2.5	.010	.0012
27.5	10:45	3.180	3.178			
				2.5	.012	.0016
25.0	11:30	3.190	3.190			

Gyrosyn or Horizontal Gyroscope

The horizontal gyroscope, or Gyrosyn, is the instrument that has been selected for measuring azimuth, that is indicating the direction of travel. It operates on 115-volt, 400-cycle-AC, 3-phase current and 28 volts of DC. It takes 28 watts of AC and 20 watts of DC. Its rotor spins at near 24,000 rpm. A perfect gyroscope, i.e., one where all friction is reduced to zero and perfect balance is achieved, will maintain its axis of rotation fixed in relation to its position in space. This frictionless and perfectly balanced gyro obviously is not possible of attainment. Friction and unbalance ever so little as it might be causes a gyroscope to precess, i.e., move its axis to counteract those forces.

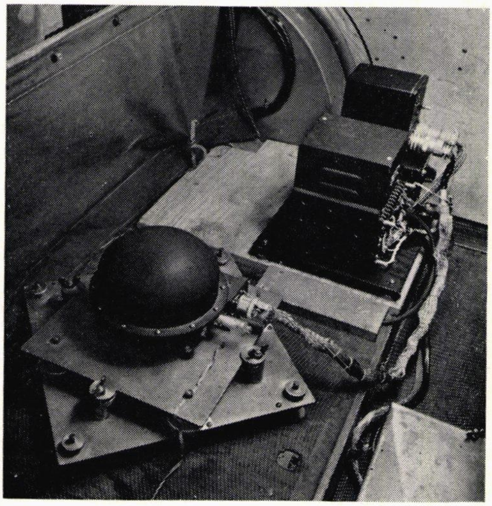


Figure 6. Installation of vertical gyroscope.

This leads to the necessity of applying certain controls on the instrument in order to cause its axis to remain fixed. The earth's magnetic field furnishes a very handy reference to use for this purpose. It is relatively static and bears a constant relationship to true north within the area of any project we are likely to devise.

Just how the gyro-rotor axis is caused to keep its alignment fixed in relation to the earth's magnetic field is understandable generally only to those with a more than ordinary knowledge of electricity, so its detail will be covered but sketchily here. The flux valve, or the ball that is mounted about 3 ft. above the top of the vehicle, contains the instrument that accomplishes this. It senses the earth's magnetic field and transmits it to a signal selsyn in the gyro housing, that in turn, electrically causes a force to be applied to the proper gimbal forcing the axis of the rotor to align itself with the magnetic field.

When the axis is correctly oriented that fact is made known by what is called an annunciator that shows in the upper-right corner of the face of the gyrosyn. This annunciator alternates from a dot to a plus sign when the axis is aligned, indicating that forces are being applied on both sides of the gimbal alter-

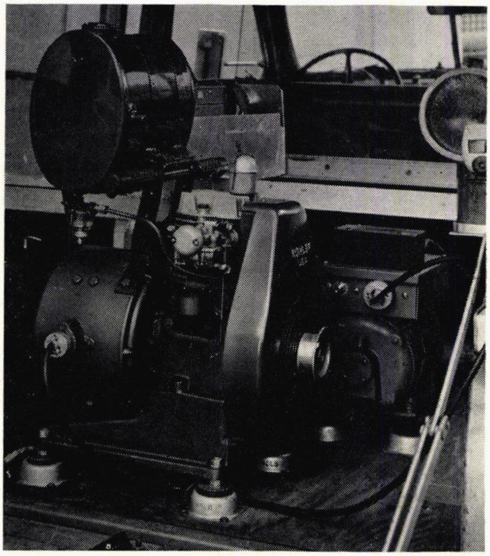


Figure 7. Generator and converter installation.

nately and in the same relative amount. This annunciator has a dual purpose: it not only indicates that gyro axis is aligned properly (by its alternating dot and plus), but it also indicates whether a field is being encountered where the magnetic lines of the earth are disrupted or abnormal. Such an abnormality will cause either the dot or the plus sign to appear constantly, according to which way the new magnetic lines are causing the axis to be moving. When this situation exists or when it is feared that it might happen, the influence of the flux valve is cut off by means of a switch and when the disturbance is over, the flux-valve influence is cut back in, and a check is made that the signal alternates before making further azimuth readings.

While running with the control cut off,

the gyro will precess at a rate proportional to its friction and unbalance. However, this rate is reduced by proper maintenance to be less than roughly ½ deg. in 5 min. This causes little concern for the areas of abnormal influences of the earth's magnetic lines are not large and are passed through rather quickly.

A test of the accuracy of the gyrosyn, or horizontal gyroscope, was made by taking the equipment to the local airport and aligning it four times on each of twelve directions.

Table 2 indicates that in each of 72 comparable pairs the maximum difference in observed readings was 1 deg. When comparing the average reverse azimuths with the average forward azimuth the maximum difference was ⅞ deg. These results are good when one considers that the dial of the gyrosyn is graduated only to 5-deg. increments.

TABLE 2

Magnetic Azimuth of Rose	True Azimuth	Recorded Observations				Max. Diff.	Average Observed Azimuth	Reverse Azimuth (Average) −180°	Diff.
		1st	2nd	3rd	4th				
0	18	17	17½	17	17	½	17⅛	16½	⅝
30	48	46	47	47	47	1	46¾	46	¾
60	78	76	76	77	76	1	76¼	76⅛	⅛
90	108	106	106½	107	107	1	106⅝	106½	⅛
120	138	137	136	136	136	1	136¼	137⅛	⅞
150	168	167	166	166	166	1	166¾	167¼	½
180	198	197	196	197	196	1	196½		
210	228	226	226	226	226	0	226		
240	258	256	256½	256	256	½	256⅛		
270	288	287	287	286	286	1	286½		
300	318	317	317½	317	317	½	317⅛		
330	348	347	348	347	347	1	347¼		

When the original recordings are considered, then 7 of the 24 comparable pairs differ by no degrees from the reverse azimuth in the same series of observations. It is also found that 2 differ by ½; 12 by 1; 2 by 1½; and 1 by 2.

The stated declination of the gyrosyn was 17½ deg. The recorded information indicates that this figure is high and that about 16½ deg. is a more reliable figure. The declination setting, however, is not critical as traverses are adjusted to established control stations and proper corrections are made.

Vertical Gyroscope

The installation and operation of the vertical gyroscope posed greater problems than did that of the horizontal gyroscope. For one thing, it was desired that the grade and superelevation be recorded in percent. This is equivalent to reading an angle of less than half a degree. The gyro axis is but some 3 in. long, and a half degree of movement means about 0.01 in. in actual displacement.

As previously explained, a perfect gyro is not possible of attainment. Friction and unbalance forces tend to move its axis of rotation. We must apply controls on the vertical gyro to keep its axis plumb, for it is the deviation of the plane normal to the plumb that gives the grade and super readings.

Mounted on the top of the gyro axis gimbals are two level bubbles, one on the long axis of the car and the other at right angles to it. These bubbles are bridged with an electric current, that is, an electric terminal is drawn out of each end and another terminal is drawn from the middle. The liquid in the level tube is a conductor of electricity and as long as the bubble remains center an equal amount of current flows from the center terminal to either of the end terminals. However, when the bubble is displaced, more current flows through the terminal away from the bubble. This causes a force to be applied to the proper gimbal to erect the axis and bring it back to the vertical. There is no way of detecting whether the vertical reference is truly vertical or not. This gyro is housed in a metal case and the operation of it cannot be observed. And if it could be observed, it is not likely that one could detect what would be an appreciable error in this vertical reference.

Conceivably, if the two bubbles explained were depended upon solely to keep the gyro axis plumb, then situations of acceleration and deceleration, or turning curves with the incident lateral forces, would cause disturbances that would tend to force the vertical axis out of plumb. To take care of these conditions another set of bubbles parallel to the two mentioned are placed on the same gyro gimbal. These bubbles, when molested by acceleration or deceleration or lateral turning forces, cause a relay to be tripped which cuts out the effect of the primary control bubbles, and the gyro runs free for the period during which that situation exists. And as before when running free, the gyro precesses according to friction and unbalance forces. The conditions that cause these disturbances exist for periods of very short duration when it is realized that the rate of travel is around 5 to 10 mph.

There is one situation that occurs occasionally which causes some trouble. That is the case where a level bubble may separate into two or more smaller bubbles and remain that way for some time. In this case our vertical reference is allowed to tip to one side or the other and the readings become in error. This situation can be detected by the realization that the grade and super readings are unrealistic. The two inclinometer tubes furnish a ready reference that aids in the detection of this situation.

Another situation that causes some trouble is sticking relays. When they stick the gyro is allowed to run free long enough to throw the vertical axis appreciably out.

It is necessary to take all the spring action out of the vehicle to get true grade and super readings. If this were not done, variations of loading would change the car body with respect to the axles and readings of grade and superelevation would be appreciably in error.

When the spring action is taken out of the car the vibration is necessarily increased, making it harder to take notes and limiting the roads over which the vehicle can be operated.

Experimental loading and test operating on various grades indicates that variations from the true grades seldom are more than 2 percent and generally stay within 1 percent when the springs are not tied down. When grade and superelevation results of a higher degree of accuracy are not needed, the equipment is operated without taking out the spring action.

A test designed to determine how consistent readings were in regard to grade and super with spring action taken out was conducted on a mile of road in El Dorado County. The test consisted of marking the exact position of the vehicle on 100 locations on a mile section of road and making readings of the grade and super on four separate passes of the vehicle. The detail of this test is outlined in a document on file at the Highway Planning Survey Office entitled "Test #1 Gyroscopic Equipment," December 18, 1950. Among other things it was shown that the greatest variation of any two of four grade readings at a given location was 1.3 percent. These variations are:

Maximum Variation Four Readings	*Number of Locations*
0.0%	—
.1	—
.2	—
.3	5
.4	14
.5	22
.6	15
.7	12
.8	12
.9	6
1.0	7
1.1	3
1.2	3
1.3	1
	100

FIELD OPERATION

Two men operate the equipment in the field. The party chief acts as driver and selects all the points at which observations are to be made. At these points he reads the various instruments and the assistant records all the data on a special form, shown as Figure 1, especially designed so that subsequent IBM procedures are facilitated. The manner in which this field work is accomplished is roughly as follows:

The general information such as road description, date, personnel, time, etc., are recorded in the Notes section of the form; the odometer is set to zero and movement is started forward. As each change of alignment detail is encountered, the odometer position of that change, the identifying code describing the change, and the azimuth of the new direction is recorded in the proper column of the form. In regard to curves the odometer position of their beginning and the proper code that is CR or CL indicating a right curve or a left curve and an entry in the superelevation column is made. At points of reverse or compounding the odometer position, a proper code for the situation and an azimuth reading is recorded.

In respect to grades, the odometer position of the estimated intersection of the grades extended is recorded, but the actual grade is not read for that position until the maximum or minimum grade is reached. This gives information needed to roughly calculate the elevation at any point along the route. It has been found difficult to identify beginnings and endings of vertical curves and there is no quick way of calculating the elevation of points on them.

In order to properly orient the traverses, the position of every available triangulation station encountered is noted. In fact, special traverses are run to such positions if they are not too far out of the way. Triangulation stations are known geodetic positions established by precise survey methods. Locations of and data from all bench marks are also

COMPARISON OF AVERAGE GRADES AND ELEVATIONS ALONG US 101 FROM GOLDEN GATE BRIDGE TO THE OREGON STATE LINE.

U.S.G.S. ELEVATIONS V'S GYRO TRAVERSE COMPUTATIONS.

DESCRIPTION	LOCATION TRAV ODOM	INTERVENING DIST.	ELEVATIONS IN FEET RECORDED BM'S	GYRO TRAV. CALCULATIONS	DIFFERENCES IN ELEV BET BM'S IN FEET BM'S	GYRO	AVERAGE GRADE BETWEEN BM'S IN FEET BM'S	GYRO	DIFFERENCE IN AVERAGE GRADES GYRO MINUS TRUE
1. GG Br Deck	85 00.000		241	241					
		21.357			-224	-371	-.19	-.33	-.14
2. Approximation	85 21.357		17	-130					
		112.021			+1346	+1352	+.23	+.23	.00
3. Willits	78 1.325		1363	1222					
		12.456			-182	-116	-.28	-.18	+.10
4. USGS Q-103	126 12.215		1181	1106					
		2.742			+107	+112	+.74	+.77	+.03
5. USGS N-103	126 14.957		1288	1218					
		14.914			+210	+337	+.27	+.43	+.16
6. USGS C-103	126 29.871		1498	1555					
		3.621			- 29	+ 47	-.15	+.25	+.40
7. USGS A-103	126 33.492		1469	1602					
		12.476			-509	-380	-.77	-.58	+.19
8. USGS S-102	126 45.968		960	1222					
		4.300			-294	-243	-1.29	-I.07	+.22
9. USGS P-102	126 50.268		666	979					
		9.020			-133	+140	-.28	+.29	+.57
10. USGS H-102	126 59.288		533	1119					
		.634			+ 37	+ 64	+1.11	+1.91	+.80
11. USGS G-102	126 59.922		570	1183					
		2.96[illegible]			-104	- 35	-.66	-.22	+.44
12. USGS E-102	20 1.252		466	1148					
		8.254			+101	+ 7	+.23	+.02	-.21
13. USGS Y-101	20 9.506		567	1155					
		14.828			-236	-371	-.30	-.47	-.17
14. USGS L-101	21 14.507		331	784					
		2.490			-125	- 95	-.95	-.72	+.23
15. USGS J-101	22 1.992		206	689					
		7.708			- 31	- 88	-.08	-.21	-.13
16. USGS E-101	22 9.700		175	601					
		20.276			- 21	- 6	-.02	-.01	+.01
17. USGS S-100	24 5.006		154	595					
		5.390			- 92	- 55	-.32	-.19	+.13
18. USGS N-100	25 2.595		62	540					
		7.416			- 29	+ 42	-.07	+.11	+.18
19. Approx	27 2.040		33	582					
		9.870			- 29	+ 77	-.05	+.15	+.20
20. Approx	27 11.910		4	659					
		37.279			+ 8	+111		+.30	+.30
21. Approx	33 8.740		12	770					
		9.260			+ 3	+ 21	+.01	+.04	+.03
22. Approx	33 18.000		15	791					
		2.975			+ 18	- 64	+.11	-.41	-.52
23. USGS J-74	34 .992		33	727					
		1.393			+ 6	- 9	+.08	-.12	-.20
24. Approx	34 2.385		39	718					
		2.239			+ 24	+ 39	+.20	+.33	+.13
25. USGS G-74	34 4.624		63	757					
		6.742			+409	+422	+1.15	+1.18	+.03
26. Approx	34 11.36[illegible]		472	1179					
		7.276			+ 10	+212	+.03	+.55	+.52
27. USGS A-74	79 3.537		482	1391					
		2.235			-439	-438	-3.72	-3.72	
28. USGS Z-73	79 5.772		43	953					
		7.231			- 26	+113	-.07	+.30	+.37
29. USGS W-73	79 13.003		17	1066					
		24.780			+ 46	+437	+.04	+.33	+.29
30. TRI STA HYTREE	82 9.695		63	1503					
TOTAL		374.149			-178	+1262	-.009	+.064	+.073

JTMcWiehl 1-28-52 IT-5532

CALIFORNIA STATE-WIDE HIGHWAY PLANNING SURVEY

Figure 8. Comparison of average grades and elevation along US 101 from Golden Gate Bridge to the Oregon state line.

recorded. These serve to give an idea of the accuracy of the work done in the vertical sense.

IBM PHASE OF THE GYRO-SURVEY OPERATION

In order to make the gyro-type of survey a practical procedure, it is necessary to devise a mass mechanical method of calculating the field notes of the traverses. When it is considered that the 680 mi. of traverses in Humboldt County meant the taking of 24,000 observations, their calculation by ordinary methods would take quite a time. A short-cut method has been devised such that roughly within a week a tabulation showing certain data can be produced. This tabulation includes a great deal of information, most of which is mechanically calculated from the notes as shown on the field sheet form. For instance, machine processes give: (1) azimuth of the chord, (2) central Angle of Curve, (3) intervening distance, (4) length of chord of curve, (5) radius of curve, (6) safe driving speed on curves, (7) departures or X values, (8) latitudes or Y values, and (9) elevations in feet, all from the field note detail previously given.

Without going into too much technical detail of just how these calculations are done on the machines, a brief review of each one is outlined.

Azimuth of the Chord

The azimuth of the chord is gotten by adding to that azimuth at the beginning of a curve, the azimuth upon leaving, and then dividing by two.

There are certain complications that enter into the picture when the entering azimuth and the leaving azimuth are on opposite sides of 0 or 360 deg. These complications are not great and it is only necessary to add 360 deg. to the azimuths and then divide by two. Cases where the angular turn is greater than 180 deg. are relatively few and are handled manually.

Central Angle of Curve

The central angle of the curve is gotten merely by subtracting the two azimuths, the entering azimuth and the leaving azimuth. Again special consideration must be made for the central angle that embraces the transition from 360 to 0 deg.

Intervening Distance

Intervening distance is gotten by subtracting the beginning odometer from the ending odometer of the recorded section concerned.

Length of Chord of Curve

For every given central angle of a curve there is a definite ratio that the length of the chord bears to the arc or circular segment. By matching these ratios to the central angles by groups, mass calculations are made on the arcs or curve intervening distance, and the length of chord is established. This length is necessary in order to convert all points of recorded data to equivalent X and Y coördinate values.

Safe Driving Speeds on Curves

The formula[1] for estimating safe driving speeds on curves might seem to pose difficulties in the IBM mechanical calculation machines. This is not so, for the 602 calculating punch machine can do an unbelievable number of additions, subtractions, multiplications, and divisions, take the result and operate upon it, etc. This makes the calculation of the expression $\frac{R(S - 0.16)}{0.067}$ a very simple one. However, though it can be made to do it, the operation of extracting square root is not a practical operation for the number of curves that are encountered in a project. Instead the results of the above expression are sorted in like value piles and the proper speed is punched on the cards by consulting a table of squares.

Radius of Curves

As in the chord-length calculation there is a definite ratio for each central angle that expresses the relationship of the radius to the arc length. Like central angles are selected, an operation is made on the arc length, and the result is the radius.

[1] $V = \sqrt{\frac{R(S - .16)}{.067}}$

where V = safe driving speed in mph
R = radius of curve in feet
S = superelevation in percent and
0.16 = friction factor.

Departures and Latitudes or X and Y Coördinate Equivalent Length

At this stage of the procedure all travel has been reduced to equivalent straight lines of which the corresponding direction of travel is known. Knowing these distances and directions, all that is left to do is to apply the proper trigonometric function and reduce all the distances to the X (east–west) equivalent and the Y (north–south) equivalent. By tabulating a progressive total of these distances a scalable trace is gotten (expressed in 0.001-mi. coördinates) of the actual route covered.

Now in this respect, if the vehicle is brought back to the point of beginning, axiomatically it has gone as far east as it has west, or it has gone as far south as it has north, and the algebraic sum of the latitudes and departures should be zero. If it happens that this algebraic sum is not zero, then the difference or error is taken and applying a proper factor it can be distributed proportionately through all the legs of the traverse concerned.

Elevation in Feet

A machine calculation that applies the grade against the distance traveled gives a figure representing the elevation at all points. These results can be accumulated and what is seen on the tabulation is a grade profile of elevations expressed in 0.1 ft.

DRAFTING THE FINAL TRAVERSE

The final phase of the series of events is that of drafting and tracing a reproducible copy. Coördinates of the trace are gotten from the furnished completed tabulation. These are plotted on 10-by-10 cross-section paper, usually at a scale of 10 in. to the mi. This is a convenient scale, because the coördinate-alignment positions are given in 0.001 mi. which makes each inch 0.1 mi. and each 0.1 in. represents 0.01 mi., and so on. As each curve is encountered on the tabulation, the radius is scaled off on dividers and the center of curve established. The curve is then drawn in on the hard copy. Tangents between proper points are drawn and topographic detail shown in the Notes section of the tabulated traverse. The grade elevations are likewise plotted and plotted points connected. This resulting "hard copy" is then traced to convenient sheets embodying strips of complete administrative sections or is traced in sheets of standard size, whichever is the most convenient for the use intended. An example of a piint from a portion one of the traverses is shown in Figure 3.

FIELD TEST OF EQUIPMENT

Three controlled tests have been made with the equipment to determine the accuracy that might be expected of the various instruments. The detail of these tests is on file at the Highway Planning Survey Section of the Department of Public Works and information concerning them is available upon request:

Test 1 was designed to determine whether the various instruments would consistently read the same when the car was brought back repeatedly to the same identical position.

Test 2 was an operational type run of a selected 4.251 miles of Highway US 50 upon which accurate plans were available. It was designed to determine the accuracy that might be expected in the operation of the equipment considering the human element and under simulated operating conditions.

Test 3 was designed to determine the error of closure that might be expected on completing a closed circuit of travel. Two circuits were chosen and each was run three times. The field notes were calculated by IBM machine methods and closures determined from coördinates furnished in their results.

PRACTICAL APPLICATION OF TECHNIQUE

Some 10,000 mi. of state highways and county roads have been gryo traversed using the techniques outlined in the body of the report. Some of this mileage was traversed in order to assist the road inventory parties in establishing the proper alignment of roads on county maps. Some was run in order to provide certain statistical detail for special legislative reports. A great amount of the mileage was run to provide information that when combined with other data formed the basis for an extensive highway deficiency study. Still other mileage was run in a research sense.

The accuracy of the results of the operations are quite satisfactory as is shown by the horizontal closures obtained on several large closed circuits. It is interesting to note a few of these.

Circuit	Miles	Error	
		In Miles	In % of Total
Roseville Lincoln Newcastle #1	33.1	0.04	0.1
#2	33.1	.1	.3
#3	33.1	.1	.3
San Bernardino County #1	85.9	.4	.6
#2	5.3	.1	2.1
#3	29.3	.4	1.4
#4	9.1	.1	.6
Humboldt #1	123.2	1.4	1.2
#2	80.0	.4	.6
#3	38.5	.2	.6
#4	135.9	1.1	.8
#5	99.3	1.0	1.0
#6	136.1	.8	.6
#7	6.3	.1	1.6

It is noted that the percent of error of closure varies from 0.1 to 2.1 percent. The magnitude of these errors of closure should not be looked at with too much alarm as a factor can be introduced in the mechanical calculating process and they can be reduced as previously explained. However, such errors may occur or accumulate in traverses that are not closed. For these traverses, corrections can be made based on the established position of triangulation stations that may have been encountered. If such stations are not available, then the traverse should be run a second time either in the same direction or the reverse direction and a correction made based upon such a circuit.

In respect to the accuracy in regard to the taking of grades, experience to date indicates gratifying results. On a portion of US 101 that was run from the south to the north line of Humboldt County, a distance of 137 mi., a calculated difference of 38 ft. in elevation from the true was noted. When the total 385 mi. of US 101 from San Francisco North to the Oregon State Line was considered, the error in elevation between point of beginning at the Golden Gate Bridge (elevation 241 ft.) and the USGS Azimuth Mark HYTREE in Del Norte County (elevation 63 ft.) as registered by the Gyro notes was an aggregate of 1440 ft. The distance between these points is 374 mi. A comparison between the elevations as calculated by the Gyro Traverse notes and the elevations of encountered USGS BM elevations from the Golden Gate Bridge to the Oregon State Line along US 101 is shown in Figure 8.