DESIGN AND IMPLEMENTATION OF A SYSTEM TO RECORD DRIVER LATERAL POSITIONING

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An important indicator of driving performance is steering or tracking accuracy. Previous attempts to measure this variable have suffered from a variety of limitations. Previous attempts are reviewed, and numerous criteria are specified for an optimal tracking-system design. These criteria are used to develop a novel photooptic system that mounts on a test vehicle and continuously records lateral lane positions. The device uses a photodiode array to detect the position of the vehicle relative to the pavement shoulder line. System design, data reduction procedures, and practical implementation considerations are discussed. System performance is demonstrated by recording driver tracking performance over shallow right and left curves. The system is sensitive to the differences in driving behavior on the 2 curves. The device is presented as a flexible, reliable, and accurate instrument for recording vehicular track.

•ONE of the most important criteria of driving performance is steering or tracking accuracy. A driver must steer his or her vehicle along a traffic lane and keep deviations to a minimum regardless of vehicle speed, traffic flow, or roadway conditions. Although the importance of this performance has been recognized for decades, practical methods for its measurement have eluded researchers. It is therefore the purpose of this study to examine alternative solutions and develop a practical, low-cost measurement system.

The purposes were threefold: (a) to identify design criteria for a system to measure vehicle lateral positioning based on a review of previous attempts; (b) to develop an electronic system to continuously record a driver's tracking behavior by using these criteria as a set of design requirements; and (c) to evaluate the resulting system in the field to determine whether it performs according to design specifications.

Early research in lateral displacement primarily attempted to determine the minimum road width necessary for safe driving. Steinbaugh [13] subjectively estimated the lateral position of vehicles on a straight, nearly level section of highway and found that the average distance from the right front tire to the edge of the pavement was 4.8 ft (1.46 m) at speeds less than 40 miles/h (64.37 km/h). When speed increased beyond 60 miles/h (96.56 km/h), the average lateral distance from the roadside was 8.6 ft (2.62 m). On the basis of these findings, he recommended a minimum roadway width of 23.5 ft (7.16 m), which is only 6 in. (15.24 cm) less than present specifications. The present roadway design width of 24 ft (7.32 m) evolved from the results of numerous similar studies.

Researchers soon recognized the subjectivity of early observational methods and turned to photographic techniques to obtain more objective data on driver performance. Thompson and Hebden [14] used a movie camera to study passing behavior. Probably the most ambitious and perhaps dangerous attempt was described by Forbes [3], who

took movies of drivers while he flew directly above them in a blimp. Although procedures such as these were an improvement over simple estimation, they did not permit determination of measurement accuracy.

Subsequently, Green (5) developed a photographic technique to measure the lateral position of a moving vehicle by taking several photographs in rapid succession. A gunsight camera was modified to mount on a bridge truss and was operated by a remote push-button switch. Target boards containing sawtooth calibration scales were photographed at each of the observation points on the highway. These boards were then removed and traffic was photographed at each of the same points. By using 2 projectors, one could superimpose the calibration scale on the traffic image, thus allowing accurate measurement of lateral position. Measurement accuracies ranged from 6 in. (15.24 cm) at the farthest location [180 ft (54.86 m) from the camera] to 3 in. (7.62 cm) at the nearest point [40 ft (12.19 m) from the camera].

In later research, Case, Hulbert, Mount, and Brenner (2) were able to increase the accuracy of Green's technique (5) to within 3 in. (7.62 cm) at distances of up to 400 ft (121.92 m) from the camera by using a more sophisticated calibration technique. Here the calibration scales were permanently inscribed on a lucite screen coated on 1 side with magnesium oxide. Edge lighting of the screen was used to permit brightness adjustment of the calibration scale for maximum contrast with the highway vehicle.

Another technique that attempted to improve on subjective observation was reported by Holmes and Reymer (7). They modified a positive-contact traffic detector to permit recording of the vehicle path at specified points on the roadway. The original device consisted of two 20-ft (6.10-m) metal strips encased in rubber so that one was superimposed over the other. The strips made electrical contact when the top strip was depressed by the passage of a vehicle. Lateral position was measured by dividing 1 of the metal strips into individual segments and running a separate wire to each. By these means, vehicle position was indicated by the particular segments making electrical contact. A major problem with this approach, however, was that the system was accurate to within only 1 ft (0.30 m). Furthermore, 2 or more adjacent sections could be activated by vehicles with wide or dual tires.

A popular technique still in use involves lining the measurement course with traffic cones and recording the number of cones touched by the vehicle (6, 12). This procedure obviously has little relevance to actual dynamic traffic situations.

Although these techniques could indicate the driver's lateral position at specific points along the road, none were capable of describing steering or tracking behavior. Considerably more measurements taken over a length of roadway were needed to achieve valid measures.

One approach to obtaining such measures would be to take actual measurements of the driving track. This technique would yield greater experimental flexibility by permitting evaluation of the effects of numerous roadway characteristics on driving behavior. For example, the effects of curves and hills on lateral positioning must be assessed by recording many measurements over a relatively long stretch of roadway.

Perhaps the earliest technique for recording the actual track was described by Brown (1). Water from a tank dripped on the rear wheels, and a movie camera photographed the resulting trial. Brown (1) reported 2 primary difficulties with the technique that led to its rejection. First, the test drivers thought that the gas tank was leaking, and second, the resulting tracking scores could not be readily quantified.

In an attempt to increase flexibility and accuracy, Michaels and Cozan (9) developed an electronic system to study the perceptual and field factors that cause lateral displacements. A row of independent photodetector units was mounted facing downward on the rear bumper of an automobile. Each detector contained a photoresistor, the output of which varied with the level of light reflected from the roadway. When a properly biased transistor was connected to each photoresistor, no output was given unless the amount of reflected light reached a specified minimum level. Thus when a single detector passed over a highly reflective line painted in the center of the driving line, that detector produced a signal. With this system, lateral displacement could be estimated to the nearest inch (2.54 cm) over a range of 6 ft (1.83 m). The Michaels and Cozan device provided several advantages over previous systems. It directly and continuously

measured the vehicle's path as it traveled down the test track, and it gave a very accurate description of the vehicle's track and required no subsequent manual calculations or time for film development. A major drawback, however, was that the system required a center-lane reflective paint strip that was clearly visible to the driver. No way was found to camouflage this line and still maintain sufficient contrast ratios to ensure reliable data from the placement detectors. Therefore, the driver's perceptual task was not the same as that for driving on normal highways. In addition, this tracking system could be used only on specially painted road surfaces and thus could not be used to make measurements on normal highways.

A more versatile tracking system was described by Matanzo and Rockwell (8). This system measured vehicle position relative to the white shoulder line. A single photo-resistor, mounted in an arm positioned on the right side of the instrumented vehicle, scanned back and forth beside the vehicle and produced a large resistance change whenever the photodiode sensed the highly reflective shoulder line. Lateral position could be assessed by determining that point in the sweep where this change occurred. Because this system used the standard white shoulder line to determine vehicle position, it did not require a specially painted road surface. It also was capable of recording the vehicular track regardless of traffic conditions or speed. Measurement accuracy was relatively high, and no manual calculations were required because the position was determined electronically.

A serious problem existed for the Matanzo and Rockwell system because it could not compensate for varying illumination levels. It therefore functioned best at night when a pair of floodlights was used to illuminate the scanned region. Because most driving and research occur during daylight, this is a major drawback. A mechanically driven scan arm also is quite sensitive to buffeting at high speeds, thus reducing measurement accuracy. System adjustments (such as increased scan rate) require additional mechanics. Recording more position measurements in one experimental condition than in another might be desirable.

A similar tracking system described by Michon and Koutstaal (10) also employed a single detector at the side of the car to measure the distance to the shoulder line. Scanning was achieved by a rotating mirror that provided 28 data points/s. This high sampling rate minimized the effects of occasional detection errors caused, for example, by wet spots. The system worked both day and night when it was used with an auxiliary light source.

This approach presented several advances over previous measurement techniques.

1. Relatively high resolution was possible.
2. It could be used over a wide range of roadway configurations.
3. It performed well over a range of environmental conditions.

However, this device also employed mechanical scanning methods that continued to limit flexibility and increased mechanical design complexity.

A major weakness of most tracking system designs has been a lack of reliability. Rockwell has stated (11, p. 159): "No method for measuring lateral placement along the highways has been reliably demonstrated." A number of alternative techniques have been attempted, but no simple, reliable, and accurate system has resulted. Nevertheless, the designs of these previous systems have suggested a number of areas in which design improvements can be made in an attempt to attain a truly flexible system. This type of system would (a) work both day and night over a range of illumination levels, (b) contain no moving parts, and (c) permit simple, inexpensive data recording.

As noted earlier, variable scan rate is a highly desirable design element that minimizes the effects of occasional spurious data. The experimenter should have the option of making this measurement or sampling rate either independent of or dependent on vehicle speed. If it were independent, lateral position data would be recorded at a constant rate regardless of vehicle speed. If it were dependent, rate of data collection would depend on vehicle speed. This latter approach would permit, for example, the same number of position measurements to be taken over the same segment of highway

at both 30 mph (48.28 km/h) and 60 mph (96.56 km/h). Hence driving behavior at the 2 speeds could be compared point by point. Adjustable data sampling rates also would be highly desirable if measurement or sampling rate were a dependent variable. An improved tracking system also should permit rapid transfer from 1 test vehicle to another. Because driving behavior is thought to be strongly biased by the particular vehicle model used, this feature would allow the experimenter to assess the extent of such influences.

Common sense indicates certain other desirable design criteria. The tracking system data collection technique should permit automatic recording and analysis of various external events, treatments, and experimenter observations. The system should be relatively inexpensive. The design should be as simple as possible and should require few expensive components. The system should

1. Operate over existing roads,
2. Not affect driving behavior,
3. Be accurate,
4. Operate over a range of illumination levels,
5. Have a high and variable measurement rate,
6. Have no moving parts,
7. Provide for simple data recording and reduction,
8. Be inexpensive,
9. Provide for simultaneous event recording, and
10. Be transferrable among vehicles.

TRACKING SYSTEM DESIGN

The heart of this system is a photodiode array mounted in a box on the side of the car that views the white shoulder line. A lens mounted in this box receives an image from the roadway and projects the scene on the array. Each photodiode produces an output voltage proportionate to the amount of light reflected from the area of road or shoulder line it views. The higher reflectance of the shoulder line distinguishes it from the darker roadway.

Circuit Description

The central component of the system is an integrated circuit containing a linear array of 50 independent silicon planar photodiodes and an associated 51-bit shift register. Also contained are presensors and postsensors located before the first and after the last diodes.
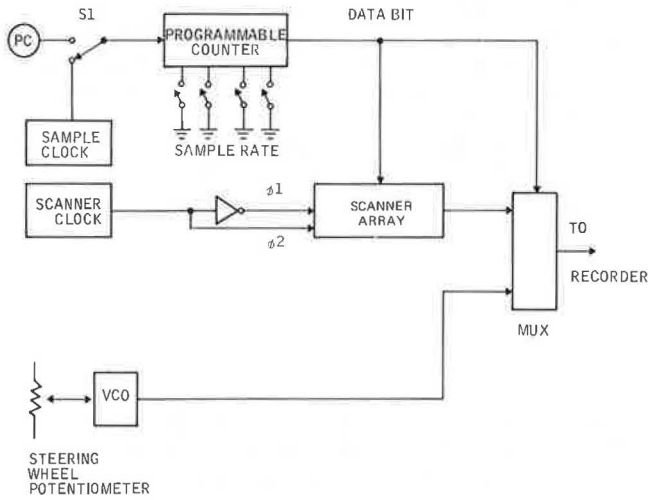
The array views the road and sequentially scans all 50 photodiodes. The sequence of output pulses varies in voltage with the amount of light that is reflected from the highway and falls on the diode being scanned. Because it is lighter than the surrounding pavement, the white line distinguishes itself by a higher reflectance and resultant higher pulse voltage.

The shift register permits a sequential output from the 50 photodiodes. As shown in Figure 1, an external clock controls the multiplexing rate.

The 50-element photodiode array also requires a data pulse to begin the sampling sequence. The frequency of this pulse determines the number of vehicle position measurements taken per second because all 50 photodiodes must be sampled to determine the position. This data-pulse frequency may be determined by either an adjustable oscillator or a wheel rotation detector on the rear tire. Thus measurement rate can be either dependent on or independent of vehicle speed.

The wheel-rotation-detector approach consists of a single photodiode mounted on the vehicle's rear fender. This detector senses a white line or piece of tape placed on the tire sidewall. As the wheel rotates, the photodiode increases its output voltage each time the white strip passes. The frequency of this pulse therefore is controlled

Figure 1. Tracking system.

directly by vehicle speed. The switch (S1 in Figure 1) selects either the oscillator or the rotation detector. When normalized, wheel-pulse frequency very accurately indicates vehicle speed.

To increase system versatility, a variable modulo counter permits division of the data-pulse frequency by any number from 1 through 16. Hence the frequency of lateral position measurement may be changed easily. In this case, it is done by switches in the car.

Because clock frequency exceeds data-pulse frequency by 50, a dead period occurs between each data series transmittal. This interim provides a convenient time to transmit information about the steering wheel position. Measurements of steering wheel position are made by a potentiometer connected to the steering column. Adjustments in resistance that are due to steering motions may then be transformed into frequency changes by a voltage-controlled oscillator. As the resistance of the oscillator input changes, the frequency of its output changes. It is this information that is introduced during the dead period of the data series.

The proposed tracking system can record the vehicle's lateral position, speed, and driver steering motions on a single-channel recorder. No moving parts are employed, and the experimenter may change the rate of sampling with the flip of a switch. All components, except those in the array, are relatively inexpensive and readily available. The system output is compatible with any high-quality AM recorder or wide-bandwidth FM recorder.

Optical System

An optical system that uses a relatively inexpensive 16-mm C-mount movie camera lens projects an image of the road surface on the linear diode array. A wide-angle (10-mm focal length) lens yields a measurement range of 41.88 in. (1.06 m) in the current configuration.

The photodiode array, housed in a dust-proof, electronically shielded container called the optical assembly box, mounts on the right side of the test vehicle just above the passenger door. A metal plate covers the side facing downward toward the shoulder white line. A C-mount lens thread centered in this plate just over the photodiode array inside the box permits rapid lens changes if necessary.

The sensitivity of the photodiode array is so great that a Wratten II neutral density filter is needed to prevent diode saturation at high light levels. With the filter removed, sensitivity is sufficient to allow normal operation, even at twilight.

Mechanical Design

A luggage rack anchors the photodiode array and optical system to the vehicle. This rack consists of 2 horizontal steel bars that connect to the automobile roof gutters. A 2 by 4-in. (5.1 by 10.2-cm) wooden beam mounts atop each of the 2 racks, and these

structures are then joined by 2 wooden braces to form a rigid rectangular unit. The front wooden beam extends beyond the sides of the steel rack assembly to allow a mounting area for the photodiode array circuit box. The luggage rack size is adjustable from beneath, and thus, the tracker mounting system may be adjusted for most vehicle models. The system mounted on the test vehicle is shown in Figures 2 and 3.

Electronic connections with the photodiode array are made by multiple-pin connectors mounted on the rear of the optical assembly box. Interconnecting cables enter the car through the top of the right front passenger window and travel to the rear seat where all of the peripheral circuitry is located.

IMPLEMENTATION

Calibration

Each of the 50 photodiodes is independently calibrated by drawing a line between the right sidewalls of the front and rear right tires and by measuring the perpendicular distance from this line to the pinpoint of light activating each photodiode.

Recording Techniques

The output signal from the tracking system may be recorded on either an AM or FM tape recorder. In this study, an AM system was chosen because it is much less expensive than an FM system. The composite output signal is of a relatively high frequency and requires a bandwidth capability of at least 10 000 kHz. Only the most expensive FM recorders can approach this bandwidth.

Traditional AM taping techniques are not usable because the 25-Hz measurement frequency is seen as a 25-Hz pulse, which is slightly below the low-frequency capability of the recorder. Thus the recorder introduces a certain degree of signal distortion that affects both the output signal fidelity and the accuracy of the recording level indicators. The data analysis techniques, which will be described later, are capable of coping with distortions in signal fidelity, but they cannot compensate for incorrect recording levels. This problem was resolved by presetting signal levels with an oscilloscope.

DATA REDUCTION

A computer converts each data tape from analogue to digital form for further processing. For each of the 25 position measurements taken per second, the analysis program determines which of the 50 photodiode output voltages represents the inside edge of the white line. This signal is then translated into the distance in inches (centimeters) from the outside edge of the right front wheel to the inside edge of the shoulder line according to the 50 previously described calibration distances.

Because the tracking system is adjusted to make 25 position recordings each second [representing about 1 data point every 3.81 ft (1.16 m)] at 65 miles/h (104.6 km/h), excessive amounts of data are amassed at this measurement rate. To overcome this problem, medians are calculated for each successive group of 8 measurements. A cathode-ray-tube display plots sequential groups of 40 median data scores, and suspicious data are deleted by typing their assigned number on the computer keyboard. All subsequent statistical analyses are then performed on these edited median scores.

SYSTEM PERFORMANCE

The system is relatively easy to operate. After it is turned on and calibrated, it requires no further attention until data collection is completed. Measurement accuracy

Figure 2. Front view of tracking system mounted on test vehicle.

Figure 3. Side view of tracking system mounted on test vehicle.

is greater than 0.5 in. (1.27 cm), and all data reduction is done by using appropriate computer techniques. The system is quite sensitive and requires only small differences in contrast between the white line and the surrounding pavement. In fact, reliable lateral position measurements are obtainable from the shoulder line on concrete roads. The equipment is highly reliable; it has performed flawlessly through many hours of data collection.

The test results of 10 subjects will illustrate system performance and versatility. Each subject drove a Ford Custom 500 Sedan equipped with power steering over a 0.28-mile (0.45-km) curve on a rural 24-ft-wide (7.32-m-wide) 2-lane asphalt road. The curve was a level 3-min transitional spiral preceded and followed by straight pavement. Subjects drove both directions around the curve at a speed of 55 mph (88.51 km/h) but did not know that their track was being recorded.

Of the 1,112 median lateral position measurements recorded for both directions across all subjects, 984 yielded useful data for subsequent analyses. Eleven and a half percent of the data was lost because of tree shadows and a badly worn white shoulder line.

A number of statistics were calculated on these basic data. Mean and median measures of central tendency were analyzed. The mean lateral position for subjects driving the right curve was 31.66 in. (80.42 cm) measured from the edge of the right tire sidewall to the inside edge of the roadway shoulder line. For subjects driving in the opposite direction, the mean position was 35.31 in. (89.69 cm). Thus, the tracking system detected a difference of 3.65 in. (9.27 cm) in mean lane position on left and right curves. The median position was 30.99 in. (78.71 cm) for the right curve and was 35.16 in. (89.31 cm) for the left curve. The 2 different measures of central tendency showed the same results.

The standard deviation was calculated to describe oscillations about the mean lane position. The standard deviation averaged across all 10 subjects was 5.28 in. (13.41 cm) for the right curve and 7.05 in. (17.91 cm) for the left curve. Drivers showed greater variability in tracking behavior on the left curve.

Skew, calculated across subjects on both curves to describe the shapes of the distributions, showed little difference: 0.41 for the right curve and 0.53 for the left curve. Deviations were positively biased on both left and right curves.

Maximum and minimum lateral deviations were calculated for these 2 curves. Averaged across subjects, the maximum position was 41.66 in. (105.8 cm) from the shoulder line on the right curve and 47.68 in. (121.1 cm) for the left curve. These scores indicate that the subjects deviated 6.02 in. (15.29 cm) farther to the left on left curves than they did on right curves. Minimum lane position was 23.19 in. (58.90 cm) for the right curve and 23.10 in. (58.67 cm) for the left curve. The measurement system did not detect any meaningful differences in any subject's minimum lane position on the 2 different curves.

The value of the first position measurement recorded when the curve was entered analyzed to determine differences in initial position between right and left curves. The mean initial position was 35.63 in. (90.50 cm) for right curves and 26.07 in. (66.22 cm) for left curves. Thus drivers tracked 9.56 in. (24.28 cm) farther to the left when they first entered a right curve than they did when they first entered a left curve. The direction of this difference is opposite to that found when the average track through the complete curve was recorded. An instrument capable of recording only the driver's position on entering a curve would lead to entirely different conclusions about driving behavior than would have been made from an analysis of the complete track. The present system configuration permits measurements to be taken both continuously and at separate points along the roadway. This flexibility is necessary to properly interpret driver tracking behavior.

From this experiment, 4 basic statistics emerge as being sensitive to differences in tracking behavior. Either the mean or median may be used to describe the driver's central tendency within a section of roadway. In addition, the standard deviation seems to be sensitive to differences in lateral variability within right and left curves. Maximum lateral position is affected by the direction of curvature. And a measure of the initial position of the vehicle on entering a curve seems to be quite sensitive to the

direction of curvature. Although skew and minimum position measures were not sensitive to differences in road curvature, they could become important descriptors of behavior if other roadway characteristics are measured. For example, minimum lane position could differ for various lane widths or types of vehicles.

CONCLUSIONS

This experiment demonstrates the feasibility of using a fixed photodiode array to scan the roadway for white line detection. This highly accurate instrument performs well over existing roads and does not appear to influence driving behavior. The system is very flexible and fulfills all of the original design criteria.

The findings of this study illustrate the sensitivity of the system to basic differences in driver tracking behavior on shallow right and left curves. These differences were found by using a small number of subjects driving a full-sized, slow-response automobile with limited proprioceptive feedback. Even though the study took place on existing roads under various environmental conditions, only a small amount of data were lost. A more complete study (4) that used this measurement system showed similar driver behavioral discrimination in evaluating driver tracking performance over a variety of Interstate and secondary roadway configurations. This system, then, has been shown to be a sensitive new tool for the study of driving performance over a range of variables.

This instrument could be employed in a number of alternate ways to study driving behavior. For example, actual vehicle track data could be compared with steering wheel positioning data to validate and extend earlier research based on steering wheel movements. A frequency analysis of variously sized lateral deviations could be used to compare male and female drivers. Also, a study of tracking performance could provide useful information about the effects of age, alcohol, or drugs on driving behavior. A careful evaluation of tracking skills over various roadway configurations could be conducted to determine the potential for screening novice and accident-prone drivers. Such a study of driver skill elements could prove invaluable to driver training and licensing programs.

A new versatility in the study of driving behavior is therefore possible by recording vehicular track. The present instrument provides a flexible, reliable, and accurate means of recording this track.

ACKNOWLEDGMENTS

REFERENCES

1. I. D. Brown. Studies of Component Movements, Consistency and Spare Capacity of Car Drivers. Annals of Occupational Hygiene, Vol. 5, 1962, pp. 131-143.
2. H. W. Case, S. F. Hulbert, G. E. Mount, and R. Brenner. Effect of Roadside Structure on Lateral Placement of Motor Vehicles. HRB Proc., Vol. 32, 1953, pp. 364-370.
3. T. W. Forbes. Methods of Measuring Judgment and Perception Time in Passing on the Highway. HRB Proc., Vol. 19, 1939, pp. 218-231.
4. J. A. Gardner. Design, Implementation, and Use of a System to Record Driver Lateral Positioning on Interstate and Secondary Highways. North Carolina State University, PhD dissertation, 1974.
5. F. H. Green. Method for Recording Lateral Position of Vehicles. HRB Proc., Vol. 26, 1946, pp. 397-404.

6. E. R. Hoffman and P. N. Joubert. The Effect of Changes in Some Vehicle Handling Variables on Driver Steering Performance. Human Factors, Vol. 8, 1966, pp. 245-263.

7. E. H. Holmes and S. E. Reymer. New Techniques in Traffic Behavior Studies. Public Roads, Vol. 21, 1940, pp. 29-45.

8. F. Matanzo and T. H. Rockwell. Driving Performance Under Nighttime Conditions of Visual Degradation. Human Factors, Vol. 9, 1967, pp. 427-432.

9. R. M. Michaels and L. W. Cozan. Perceptual and Field Factors Causing Lateral Displacement. Public Roads, Vol. 32, 1963, pp. 233-240.

10. J. A. Michon and G. A. Koutstaal. An Instrumented Car for the Study of Driver Behavior. American Psychologist, Vol. 24, 1969, pp. 297-300.

11. T. H. Rockwell. Skills, Judgment and Information Acquisition in Driving. In Human Factors in Highway Traffic Safety Research (T. W. Forbes, ed.), John Wiley and Sons, Inc., New York, 1972.

12. K. U. Smith, R. Kaplan, and H. Kao. Experimental Systems Analysis of Simulated Vehicle Steering and Safety Training. Journal of Applied Psychology, Vol. 54, 1970, pp. 364-376.

13. V. B. Steinbaugh. Separating Traffic on Multiple-Lane Highways. In Highway Planning, 24th Annual Michigan Highway Conference, Michigan Department of State Highways, 1928, pp. 53-63.

14. J. T. Thompson and N. Hebden. A Study of the Passing of Vehicles on Highways. Public Roads, Vol. 18, 1937, pp. 121-137.