A System for Automatic Vehicle Lateral Guidance

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It is clear that substantial savings in both lives and personal property can be achieved through highway automation. The experimental results obtained from one phase of an automation study—automatic lateral guidance—are presented in this paper. Preliminary results indicate that the proposed system is feasible on nonreinforced roads. The problems encountered on reinforced highways have been identified and are presented in detail together with a discussion of one possible solution.

•THE network of super highways available to today's driver is growing in size at a rapid rate, and his car has been made somewhat safer by the concentrated efforts of both government and private industry. Yet, in excess of 53,000 people died on the Nation's highways last year, and the yearly cost of highway accidents has been estimated at more than $10 billion. Unless satisfactory solutions to these problems are found, these conditions can only be expected to deteriorate further. Several solutions have been proposed, such as expanded highway facilities, high-speed mass transportation, and systems for highway automation (1). It is likely that the final solution will consist of some combination of these, and possibly other, alternatives.

One of the essential parts of an overall system for fully automatic control of an automobile is a subsystem for automatic steering. An investigation of one approach to automatic steering employing magnetic fields for the road reference is discussed in this paper. An overall system description is presented, as well as preliminary results of on-road testing programs conducted during the summers of 1967 and 1968. Particular emphasis is given to the problems encountered in such a system as a result of reinforcing materials in the road, and one possible solution currently under investigation is discussed in detail.

SYSTEM DESCRIPTION

Essential Components of an Automatic Steering System

A system for fully automatic lateral guidance of a vehicle must possess three essential constituents, as follows:

1. A reference system that, in the approach described here, is part of the road. It produces a measurable quantity that can be sensed by the vehicle so that its position relative to the center of the road may be accurately determined;
2. A compatible sensor mounted on the car that measures the signal produced by the reference system and determines the extent to which the car has deviated from the desired path; and
3. A steering control system that is operated continuously on the sensed deviation signal so as to keep the car centered in the lane.

Paper sponsored by Committee on Vehicle Characteristics and presented at the 48th Annual Meeting.

These components are discussed in detail in the following three sections.

The Reference System

Reference systems may be classified into either of two general types—active and passive. Passive systems have not been tried up to this time although some have been suggested. One such system (2) would employ a painted stripe in the center of the lane. The control system would home on the stripe by tracking it with photoelectric sensors mounted on the vehicle. This system has the advantage of simplicity and relative ease of implementation. However, inclement weather and extraneous light reflected from sources other than the stripe would probably present severe practical problems. Also, a wide dynamic range of sensitivity would be required.

A second passive system (3), which has been proposed, would employ specially configured magnetic materials buried in the road. If suitable magnetic sensors capable of identifying the configuration of the ferrous materials could be designed, guidance could be achieved.

The most widely studied active reference system consists of a single cable buried in the center of the controlled lane (4). This cable is excited by an alternating electrical current that establishes a measurable magnetic field in the region over the controlled lane. Two coils are placed on the front bumper of the car to sense the strength of this field. The difference between the voltages induced in the two coils is a measure of the car's deviation from the center of the road. Experimental testing of such a system has been conducted by General Motors Corporation in conjunction with Radio Corporation of America (4) and by the Road Research Laboratory (5).

The system described in this paper is conceptually similar to the single-wire system; however, two road wires are employed instead of one, and only one coil is used to derive the lateral guidance signal.

The road reference, which enables the car to measure its lateral displacement from the center of the lane, consists of a pair of current-carrying conductors separated by a distance of 8 feet and attached, for the sake of experimentation, to the surface of the road. As shown in Figure 1, these wires establish a magnetic field, the horizontal component of which is zero at the center of the lane.

The control characteristic relating strength of the lateral component of the magnetic field to displacement from the center of the lane is approximately linear over most of the 8-foot range. This provides a wide range of displacement over which the car can be controlled.

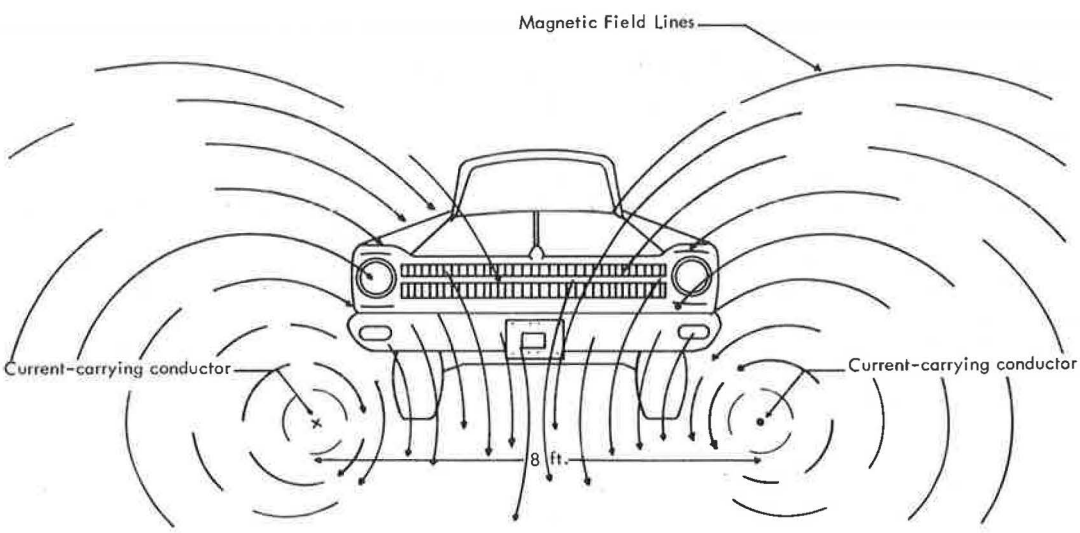

Figure 1. Magnetic field established by reference system.

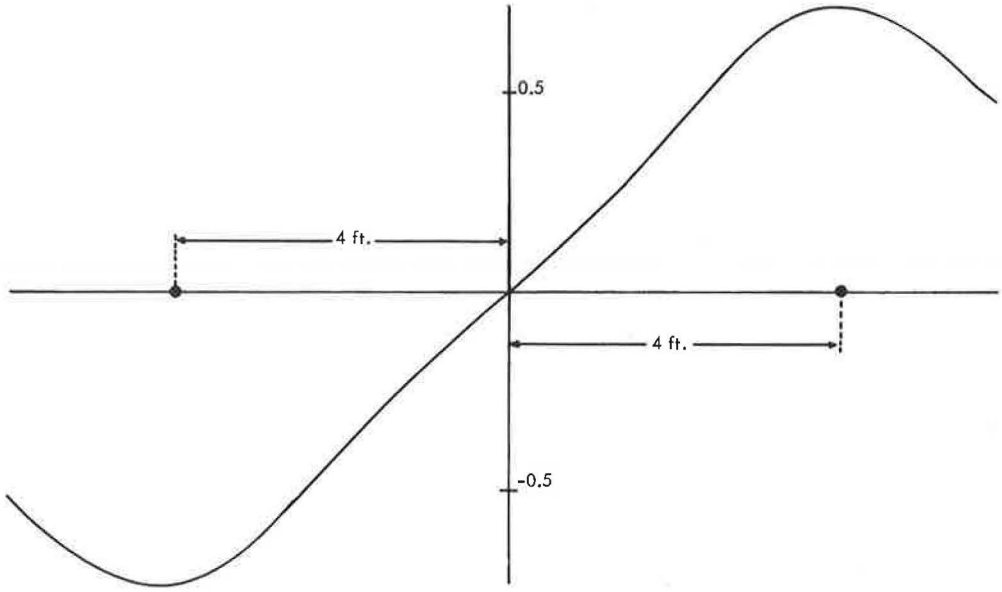

Figure 2. Measured lateral control characteristic established by reference system.

A typical characteristic measured recently on a portion of I-270 west of Columbus, Ohio, is shown in Figure 2. It is desirable that this characteristic be reasonably linear so that the corrective action taken by the car is approximately proportional to the deviation from the center of the road. Otherwise, system instability and passenger discomfort can result.

The Sensor

The second essential constituent of an automatic steering system is a sensing device mounted on the car that measures the field strength and provides an output proportional to vehicle displacement from the center of the road. In the experimental system described here, the sensor consists of a pair of coils mounted on the front bumper, one coil to measure the horizontal component of the field, and the other to measure the vertical component to obtain a time-phase reference signal. One such coil configuration employed in the study is shown in Figure 3.

Figure 3. Sensing coils for automatic steering system.

The Control System

The system that controls the lateral movement of the car on the road is easily described in terms of the block diagram shown in Figure 4. Here a feedback control system adjusts the system output—the lateral position, y, of the car—so that it is equal to the reference input, r, which corresponds to the desired position of the car. The system reduces the error, r-y, to zero so that the vehicle follows the desired path.

The amplified error signal is used to drive an electrohydraulic actuator, which

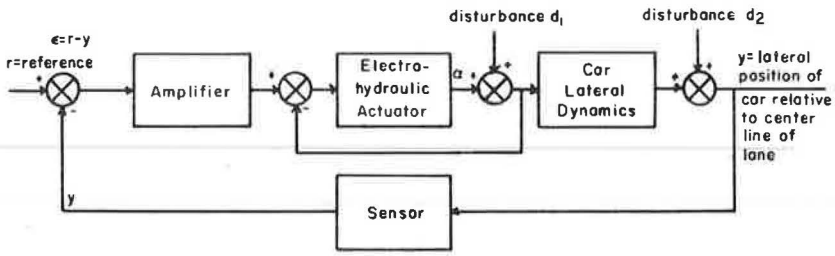

Figure 4. Lateral control system.

positions the angle, α, of the front wheels. This angle is fed back to the input of the actuator because it is essential that both the deviation of the position of the car and the angle of the front wheels are zero simultaneously when equilibrium is reached.

The lateral dynamics are the parameters that describe the characteristics of the car and that determine how it moves laterally in response to a positioning of the angle of the front wheels. Such characteristics vary among different types of cars and are dependent on such car variables as suspension, weight, tire pressure, front wheel alignment, and speed.

The disturbance, d_1, represents an undesired input to the system that rapidly changes the angle of the front wheels. An example of such a disturbance is that produced by hitting a bump or an object lying on the surface of the road. Similarly, the disturbance, d_2, represents an extraneous input, such as a wind gust, which would change the lateral position of the car.

The sensor is a device that measures the lateral position of the car and provides a voltage that is then compared to the reference voltage.

A phase-lead filter is included in the amplifier to provide an anticipation of the expected error signal. Such anticipation is required if the system is to adequately "track" a curving road.

This system was installed in a late-model vehicle in the summer of 1967 and has been undergoing evaluation and modification since that time.

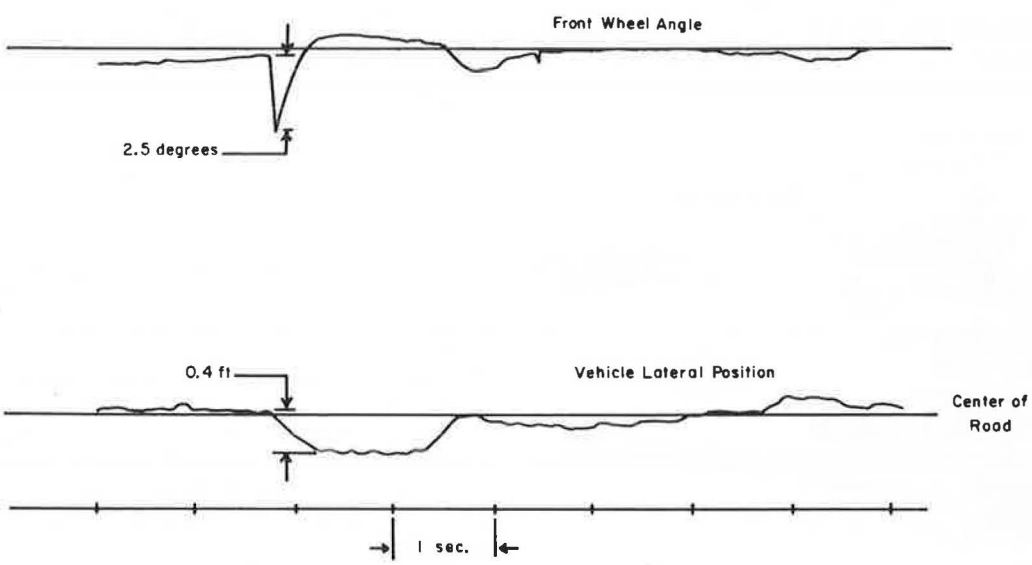

Figure 5. Experimental data showing front wheel angle and coil lateral position at a vehicle speed of 65 mph.

EXPERIMENTAL RESULTS AND CURRENT RESEARCH

Road Testing

Initial testing and evaluation of the system was conducted in the summer of 1967 on a 2-mile section of nonreinforced road. Figure 5 shows typical test data collected during those tests. The top portion of the figure displays a time trace of the angle of the front wheel immediately after an artificially induced disturbance was introduced. The lower portion shows the response of the system to such an input.

Although the disturbance was abrupt and rather severe, the car responded rapidly and returned comfortably to equilibrium in less than 2 seconds and only deviated 0.4 foot from the center of the controlled lane.

The next phase of testing of the automatic steering system was conducted in the fall of 1967 on a 4-mile length of unopened I-70. The results of this testing revealed major difficulties with the one-coil, two-wire technique when used on steel-reinforced concrete highways. It should be noted that the same problems would be encountered in any magnetic reference system.

These difficulties were due to a current that was induced in the steel-reinforcing mesh (Fig. 6) by the original magnetic field. This unwanted current in turn set up a magnetic field that alternately opposed and aided the original field.

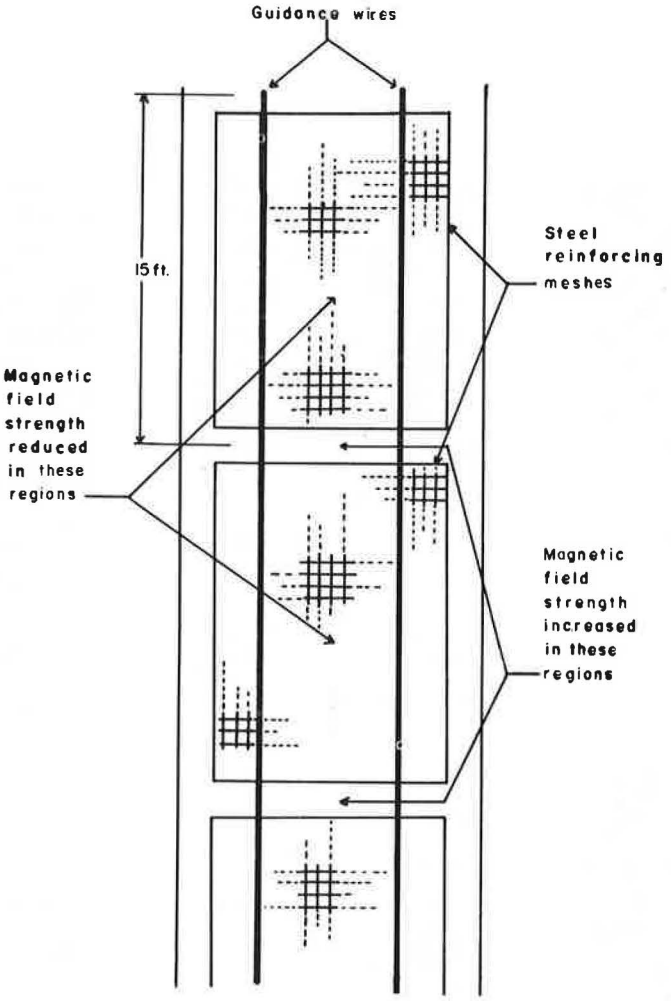

Figure 6. Location of steel reinforcing in roadway.

This phenomenon resulted in an effective time-varying sensitivity for the guidance system. Consider, for example, the hypothetical case in which the system is calibrated so that 1 volt is produced at the output of the lateral controller for a 1-foot displacement from the center of the lane with no steel reinforcing present in the road. If the vehicle were constrained to travel a path offset 1 foot from the center of the lane, a constant 1-volt correction signal would be produced.

If the same experiment were performed on a steel-reinforced roadway, with all other factors identical to those in the previous experiment, a much different result would be obtained. The correction signal would vary periodically between approximately one-half volt to more than 1 volt for every 15 feet of vehicle travel. Thus, although the car would be traveling in a straight line, the steering controller would sense that the car was moving laterally between 6 inches and more than 1 foot from the center of the road and provide lateral guidance signals accordingly.

If the automatic lateral guidance system were in operation, it is clear that an uncomfortable ride would result. The ride could be improved by reducing the gain of the amplifier shown in Figure 4; however, such a reduction would result in an overdamped system whose response would be quite sluggish. In addition, this would probably result in excessive vehicle lateral drift, especially on sharp curves.

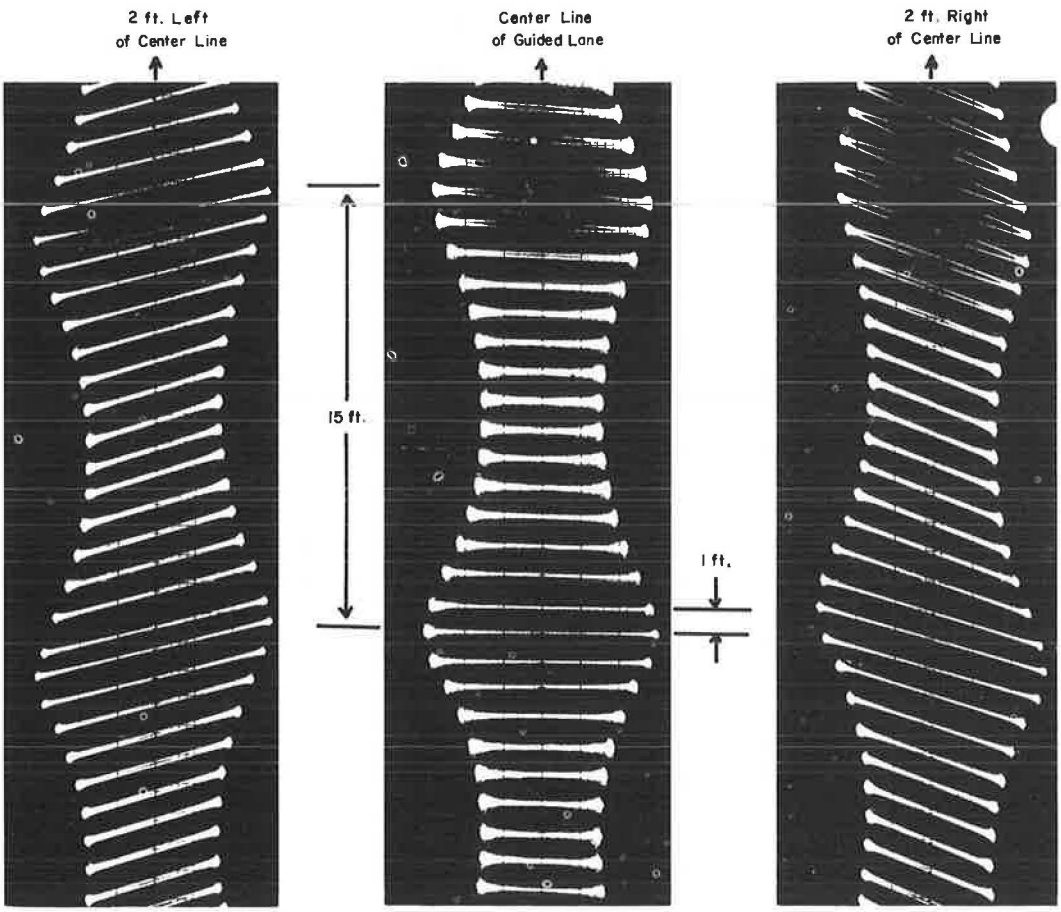

Figure 7. Lissajous' pattern representation of horizontal and vertical magnetic field components.

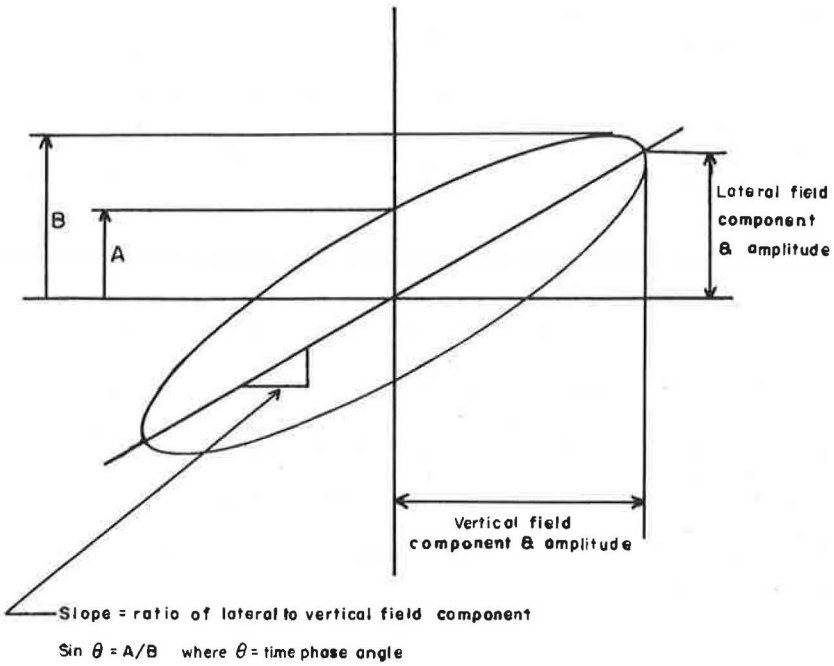

Figure 8. Typical Lissajous' pattern.

Identification of Disturbances Due to Road Reinforcing Materials

To investigate this phenomenon, the vertical and lateral-horizontal components of the resultant magnetic field were measured at 1-foot intervals on the center line of the lane and also on lines that were offset by 2 feet on each side of the center line. The horizontal and vertical field components were applied to an oscilloscope so as to produce a Lissajous' pattern (a number of these patterns are shown in Figure 7). The following three important field parameters were obtained from this pattern: (a) the amplitude of each component; (b) the ratio of these amplitudes; and (c) the time-phase relationship between the two components. One hypothetical Lissajous' pattern is shown in Figure 8. The measurements necessary to obtain the magnitude of the lateral and vertical field components are illustrated, together with the simple relationship for obtaining the time-phase between the two components.

Before making these detailed measurements, it was expected that the field strength variation could be corrected by deriving an automatic gain control signal from the vertical component of the field. This presumes that the ratio of the vertical to horizontal field components is constant at all points along the road for a given lateral offset from the center of the wires. This would be true if the slope of the major axis of each ellipse at a given offset were constant. Note from Figure 7 that the slope is not constant at a given offset. Furthermore, if one tried to use

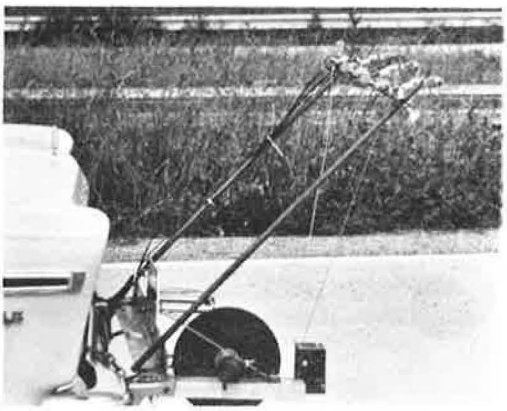

Figure 9. Auxiliary coils mounted on either side of error sensing coil.

an automatic-gain control, which is time-phase dependent, then the time phase between the vertical and horizontal components must be constant. The variations of the eccentricities of the ellipses in Figure 7 indicate that time phase was not constant with lateral displacement. Note that an asymmetry was present in the steel-mesh configuration used in obtaining the data shown in Figure 7. This caused the phase shift to be considerably greater on one side of the center line than on the other and consequently the vehicle, when laterally controlled with a phase-shift sensitive automatic-gain control, swerved severely when passing over the section of highway from which the data shown in Figure 7 were obtained.

Gain Compensation Techniques

An alternative gain compensation technique is currently under investigation and seems to offer some promise of success.

Two auxiliary coils (Fig. 9) were mounted on the test vehicle, one on each side of the lateral guidance coil, to correct the sensitivity variation. These coils sense the lateral component of the magnetic field, and the outputs of the auxiliary coils are subtracted, resulting in a net voltage, Δv, which is ideally a function only of field strength and not of lateral position on the road since the error characteristic is approximately linear. This situation is shown in Figure 10.

An Automatic Gain Control (AGC) system was considered, which employed Δv to adjust a gain, K, so that

$$K \Delta v = R$$

where R = constant reference voltage, or

$$K = \frac{R}{\Delta v}$$

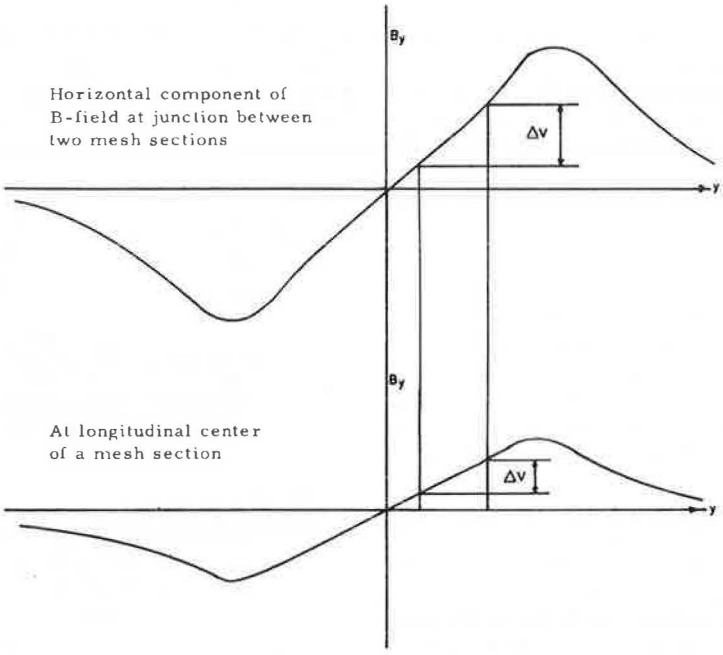

Figure 10. Output, Δv, of auxiliary coils for two different control characteristics.

This value of gain is used to equalize the lateral guidance error signal, ϵ, so that

$$\epsilon_o = K\epsilon$$

or

$$\epsilon_o = \frac{R\epsilon}{\Delta v} \tag{1}$$

An electronic circuit that performs the foregoing operation is described in the Appendix.

To determine the effectiveness of this gain control technique, the lateral component of the magnetic field was measured as a function of lateral displacement from the center of the guided lane at a large number of points along an unopened section of I-270 near Columbus, Ohio. From the resulting family of curves, the unequalized error signal, ϵ, was determined. The variations in ϵ as a function of position along the lane are shown in Figure 11a. The operation of the AGC system was then simulated by obtaining the appropriate value of Δv from the family of curves and then dividing ϵ by that value, as indicated in Eq. 1. The results are shown in Figure 11b. The spacing of the two auxiliary coils was assumed to be 2 feet.

As shown in Figure 11a, the unequalized error, ϵ, varied rapidly in amplitude at the joints between adjacent mesh sections and at the expansion joints on the bridge. In addition, it can be seen from the curves that the average value of ϵ over the bridge is somewhat less than the average value over the rest of the road.

In Figure 11b, it is seen that the amplitude variations in ϵ_o are less severe than those in ϵ and that the average value of ϵ_o over the bridge section is only slightly less than that over the rest of the road.

Since the equalized error, ϵ_o, is not a constant, it must be concluded that the basic assumption on which the AGC technique was based is not perfectly valid—that is, the guidance field is not always linear.

Consequently, it was necessary to operate the error amplifier in the AGC equalized system at a relatively low gain to obtain an overdamped response and thereby mask the error signal variations shown in Figure 11b. However, since the variations of the error signal for the equalized system (Fig. 11b) are less than those for the unequalized system, the equalized lateral control system can be operated at a higher gain with the result that the vehicle would deviate less from the center of the controlled lane for a given set of conditions.

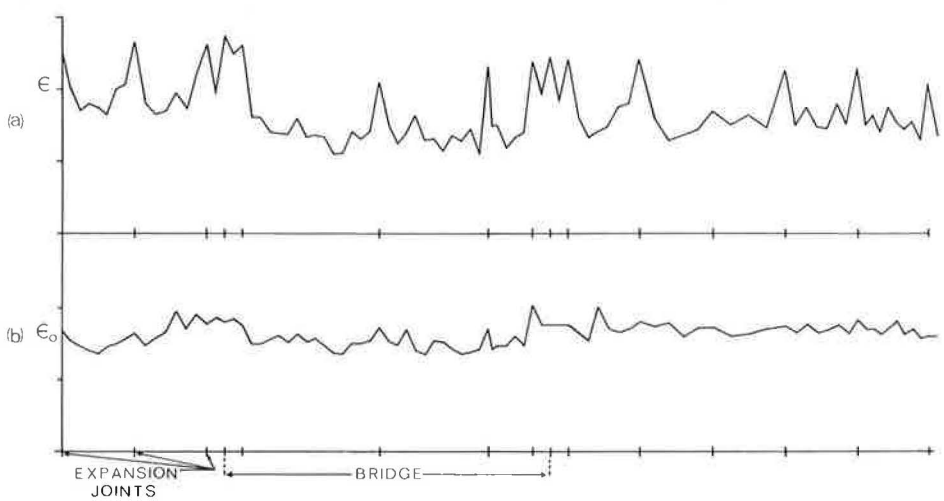

Figure 11. (a) Error signal on steel-reinforced highway for 2 feet displacement from center of lane without equilization; and (b) error signal for same conditions with equilization.

Testing of the AGC system on the automobile has been conducted at speeds up to 70 mph over the same section of road on which the field measurements were made. The error amplifier gain in the control loop was made sufficiently low so that a smooth ride was obtained. No noticeable degradation of performance was observed on the bridges; however, as the vehicle steered around a curve (radius of curvature approximately 3000 ft) at speeds approaching 70 mph, the position error became large (approximately 2.5 ft) due to the low gain.

CONCLUSIONS

Preliminary results of an investigation to determine the feasibility of full automatic lateral control of a vehicle at turnpike speeds have been presented in this paper.

A system has been designed and experimentally tested at speeds up to 70 mph on both steel-reinforced roads and nonreinforced roads. The severe problems produced by the steel reinforcing materials in the road have been isolated and clearly identified. The action of the AGC system in removing or minimizing the effects of the magnetic reference field strength variations was not completely satisfactory; however, noticeable improvement was obtained. Work on this system is continuing at the present time.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the counsel of Robert E. Fenton and the work of Ronald W. Ventola who played a very important role in the physical development and testing of this system.

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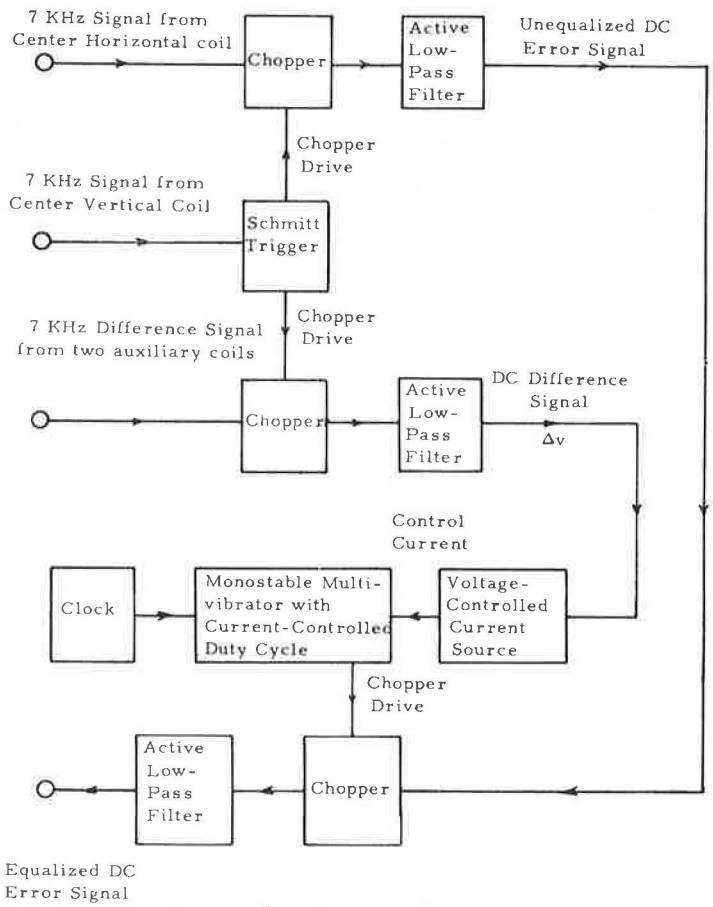
Appendix

This AGC system was implemented electronically in the manner shown in Figure 12. The upper portion of the functional block diagram represents a technique for obtaining a DC error signal. This is obtained by employing the vertical component of the magnetic field as a time-phase standard as indicated.

The lower portion shows that the signal from the two auxiliary coils, Δv, drives a voltage-controlled current source, the output of which controls a monostable multivibrator whose duty cycle is inversely proportional to the current, and thus to Δv. The output of the multivibrator provides a drive for the chopper, which samples the unequalized error signal during a length of time that is inversely proportional to Δv. The resulting signal is acted on by a low-pass filter to produce a DC error signal that is proportional to $\epsilon/\Delta v$, and hence is independent of field strength and proportional to lateral displacement.



$$\epsilon_0 = R \frac{\epsilon}{\Delta v}$$

Figure 12. Schematic diagram of gain compensation technique.