A New Vehicle Guidance and Speed Control System

ROBERT A. SPANGLER and FRED M. SNELL, Department of Biophysics, University of Buffalo

A new vehicle guidance and speed control system, using only passive roadbed equipment, is presented. The operation of the system is based on the detection of position and speed information by means of radio-frequency magnetic fields induced in roadbed loops by a vehicle-borne generator.

By suitable coupling of the guidance detector to the vehicle steering mechanism, the guidance system is made null-seeking, thus eliminating any dependence on the absolute magnitude of the signal seen by the detector. The operation of the speed control system depends on a pulse frequency derived from the spacing of the roadbed loops.

The system is shown to possess a number of advantages, including (a) passive, durable, and inexpensive road equipment; (b) individual vehicular-borne active equipment, presenting no standing wave problem and involving low power levels; (c) detection equipment entirely phase dependent rather than amplitude dependent; (d) inherent damping of lateral acceleration; (e) speed control easily subject to external moderation; and (f) the system lending itself to adequate safety features and to adaptions and additions necessary for future extended control functions, including completely programed travel.

• THE EVOLUTION of an automatic system for the complete control of motor vehicles on the nation's highways will in all probability be achieved in a step-wise fashion in regard to both the number and the nature of driving functions assumed by the control mechanism and the number of highways and vehicles so equipped. Any control mechanism adopted in the initial phases of this evolution must therefore be capable of incorporation into a more extensive automation system without obsolescence.

The purpose of this paper is to present a new system for the control of steering as well as speed for any equipped road vehicle. This new system is unique in that it depends on passive highway elements while all active components are individually born by the vehicle. These facts in themselves offer considerable advantage over a number of previously proposed systems (1 through 4) in that (a) installation of the passive highway elements would be simple, reliable, and inexpensive, and (b) both the directional and speed control are technically simple, dependent largely on individual vehicle equipment.

The proposed system would appear to be capable of immediate implementation on existing highways while serving as a functional basis for an ultimate system of more elaborate and complete control, including programed highway travel.

MODE OF OPERATION

General

In its essence the mode of operation of the proposed guidance control system depends on the detection by vehicle-borne equipment of a radio frequency magnetic field arising from closed conducting loops, horizontally located in or on the highway bed. The detector is a tuned magnetic coil with a horizontal axis perpendicular to the direction of travel. It is appropriately coupled to the steering mechanism by an electromechanical servosystem. The magnetic signal itself arises in the guidance lane loops by induction from a driven excitor coil, vehicle borne, and having its magnetic axis perpendicular to the roadbed. Thus the detector and the excitor have mutually perpendicular axes and may be adjusted to have no direct coupling. Figure 1 shows that the detector, if symetrically located within the width of the guidance lane loops, would be in a null position. Lateral deviation results in a signal whose phase relative to the excitor depends on the particular direction of deviation. After sufficient amplification and phase detection such a signal readily provides for guidance control via coupling to the steering mechanism.

The speed control system operates likewise in conjunction with the induced magnetic field arising from the guidance lane loops. The speed control detector is a tuned magnetic pickup oriented perpendicular to both the excitor and guidance control detector. Its axis is in the horizontal plane parallel to the direction of travel. Signal is thus detected only as a result of any asymmetry in longitudinal position with respect to the guidance lane loops. During the longitudinal traverse over a guidance lane loop the signal alternates in amplitude and phase; the frequency of phase reversal depends on the relative rate of travel with respect to loop size. This signal, after suitable amplification, may be used to drive an appropriate phase-sensitive pulse former whose frequency determines the vehicle throttling via an electromechanical servosystem.

Detail Theory and Mode of Operation

The guidance control detector, speed control detector, and excitor, being three mutually perpendicular coils, are mounted as an assembly beneath the vehicle anterior to the front wheel axis. It is mechanically coupled to the front wheel position so that deviation of the front wheel position towards right or left results in a corresponding and appropriately proportional displacement of the assembly.

In regard to the guidance control system, two analyses are of particular importance: (a) that dealing with the magnetic field distribution resulting from currents induced in the guidance lane loops from the excitor and (b) that dealing with the dynamic response of the system in its steering operation.

To simplify the analysis of the magnetic field distribution considerably a coordinate system is chosen with origin at the center of a particular guidance lane loop, designating the axes as shown in Figure 2. Furthermore, it is assumed that the conducting elements forming the loops have neglible diameter and magnetic permeability μ_0 is uniform in space. Finally, because the primary concern is with the magnetic field intensity along the x and z coordinates the mathematical operations may be simplified by letting the loop be of infinite length: i.e., let $b \to \infty$.

From theory the magnetic field B is related to the vector potential $\vec{A}$ by

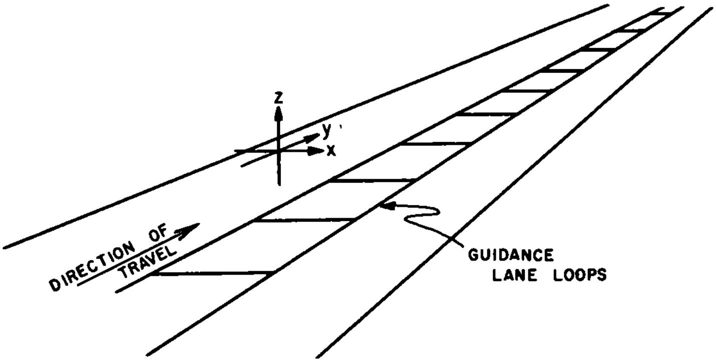

Figure 1. Three mutually perpendicular axes of excitor coil (z), guidance control detector (x), and speed control detector (y) in relation to guidance lane loops in or on highway bed.

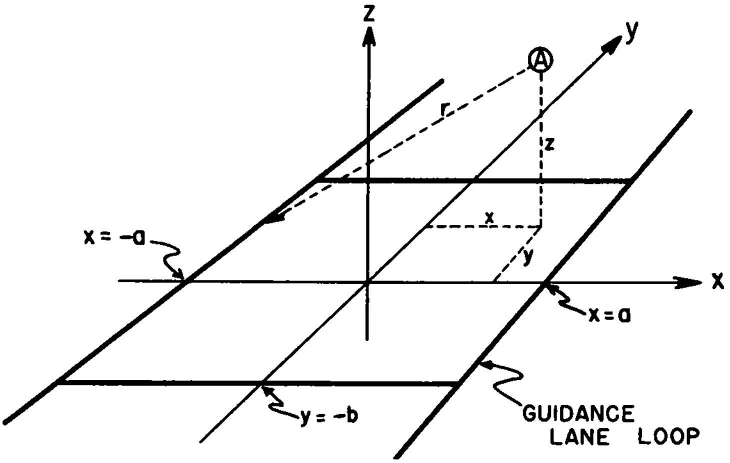

Figure 2. Coordinate system used to describe position of excitor coil and detector assembly (A) in reference to guidance lane loop.

$$\vec{B} = \nabla \times \vec{A} \tag{1}$$

in which A at a point in space is given by

$$\vec{A} = \frac{\mu_0 J}{4\pi} \int \frac{d\vec{S}}{r} \tag{2}$$

Here, J represents the total current, $d\vec{S}$, a vector element of length along the conductor at a distance r from the point where $\vec{A}$ is to be evaluated. From Eq. 2 it is evident that the magnitudes

$$A_x = A_z = 0$$

and

$$A_y = \frac{\mu_0 J}{4\pi} \int_{-\infty}^{\infty} \left\{ [\, y^2 + z^2 + (x + a)^2]^{-1/2} - [\, y^2 + z^2 + (x - a)^2]^{-1/2} \right\} dy \tag{3}$$

Integrating and taking the curl in accordance with Eq. 1 one obtains the magnitudes

$$B_x = -\frac{\mu_0 J}{2\pi} \; \frac{ax\, z}{[\, (x + a)^2 + z^2 \,]\, [\, (x - a)^2 + z^2 \,]} \equiv FJ \tag{4}$$

and

$$B_z = \frac{\mu_0 J}{\pi} \; \frac{a\,(a^2 + z^2 - x^2)}{[\, (x + a)^2 + z^2 \,]\, [\, (x - a)^2 + z^2 \,]} \equiv GJ \tag{5}$$

in which F and G, defined by the equations are functions of position. The guidance loop current, J, arises by induction from the excitor coil oriented along the z axis, and is thus a function of position of the excitor. With constant excitor current it may be assumed that J is proportional to G. Similarly, the magnitude of the signal, M, seen by the guidance control detector will be proportional to B_x or FJ. Consequently,

$$M = kFG \tag{6}$$

in which k is a combined proportionality constant.

Figure 3 shows relative values of signal amplitude M as a function of x/a for several different values of z/a. It is evident from this figure that the signal has symmetry about the origin with a phase difference of 180° on either side of this null position. It is also apparent that the signal amplitude has a maximum at some point, $x/a < 1$. In Figure 4 the relative magnitudes of this amplitude maximum, M_{max}, are plotted as a function of z/a. It is evident that the magnitude of the signal is a rapidly decreasing function of z/a, a factor of some importance in considering any extraneous unwanted magnetic fields comprising "noise" arising from highway materials.

A rotation of the guidance lane detector about the y axis may likewise lead to a situation such that a null condition may result when $x/a \neq 0$. As it turns out, because of the particular phase relations involved, this fact imposes a degree of inherent stability on the dynamics of the system insofar as any lateral acceleration of the vehicle leads to a rotation of the detector about the y axis.

In a consideration of the dynamic response of the vehicle guidance system, it is necessary to recall that the guidance detector assembly is mechanically coupled to the steering gear so as to move laterally with respect to the vehicle as the front wheels are deviated. For simplicity of analysis all factors such as response time of the mechanical steering system, tire slip and elasticity, vehicle sway, and external forces operating on the vehicle have been neglected.

Referring to Figure 5, the following terms may be defined:

S = scalor speed of vehicle (assumed constant);
L = wheelbase of vehicle;
P = distance of detector mounting anterior to front wheel axis;

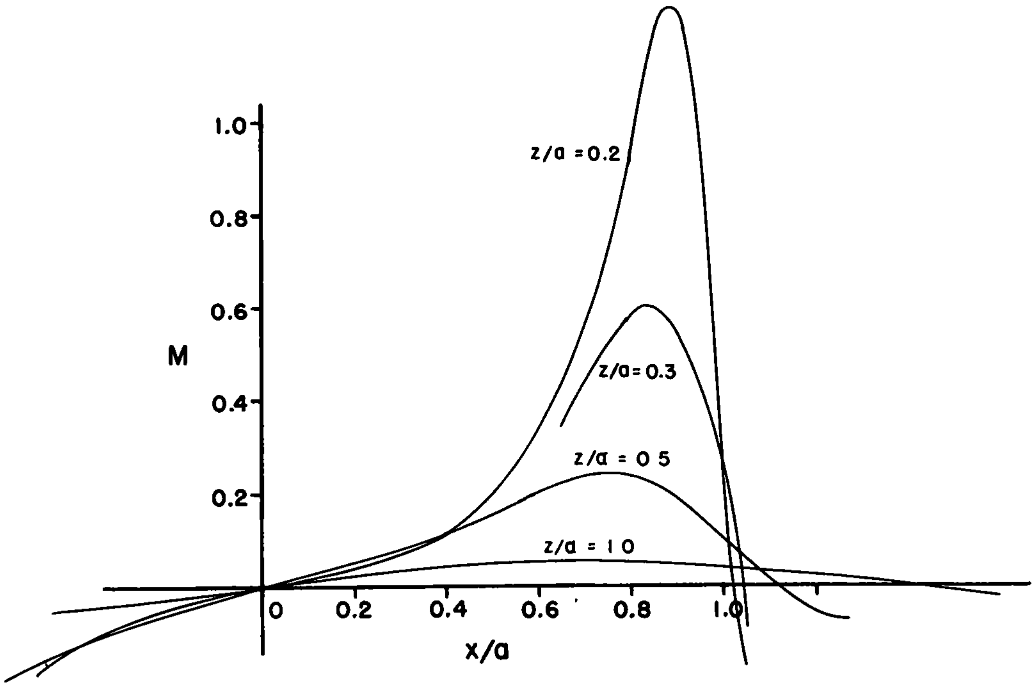

Figure 3. Plot of relative signal amplitude, M, as function of x/a at several values of z/a.

φ = angle of deviation of front wheels with reference longitudinal vehicle axis;
ψ = angle between longitudinal vehicle axis and the instantaneous tangent to control lane at detector position;
h = lateral distance of detector from longitudinal vehicle axis;
k = proportionality constant relating wheel deviation to lateral position of detector, so that $h = k \sin \varphi$;
X_f = perpendicular distance from control lane tangent to longitudinal vehicle axis at front wheel axis;
X_r = perpendicular distance from control lane tangent to longitudinal vehicle axis at rear wheel axis; and
R = instantaneous radius of curvature of control lane at detector position.

Assuming that the detector remains centered on the control lane at all times, the following four independent equations may be written on the basis of geometrical considerations:

$$X_f = h + P \sin \psi = k \sin \varphi + P \sin \psi \tag{7}$$

$$\frac{dX_f}{dt} = -S \sin (\varphi + \psi) - \frac{SP}{R} \tag{8}$$

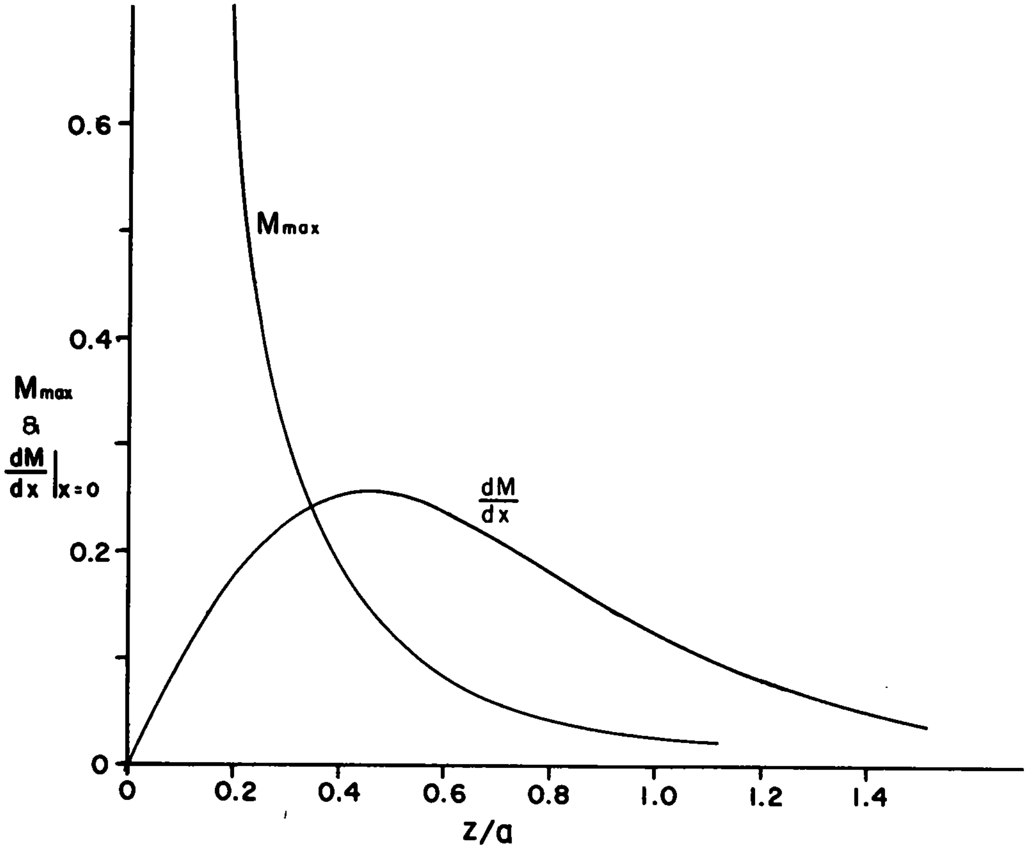

Figure 4. Plot of relative maximum signal amplitude, M_{max}, and $\left.\frac{dM}{dx}\right|_{x=0}$ as a function of z/a.

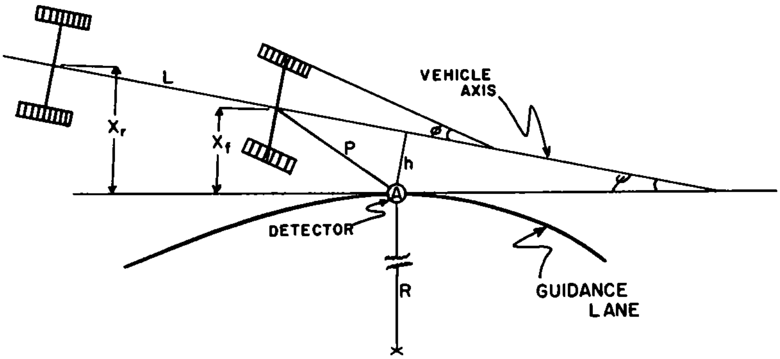

Figure 5. Drawing defining variables and system parameters used in text.

$$X_r = X_f + L \sin \psi \tag{9}$$

Assuming that ψ and φ are always small, so that $\sin(\psi + \varphi) \cong \sin\psi + \sin\varphi$, simultaneous solution of this set of equations yields

$$k \frac{d^2}{dt^2} \sin\varphi + \frac{S\,(L+P)}{L} \frac{d}{dt} \sin\varphi + \frac{S^2}{L} \sin\varphi = \frac{S^2}{R} \tag{10}$$

Holding R constant, integration gives

$$\sin\varphi = e^{-\beta t}\,(Ae^{-i\alpha t} + Be^{-i\alpha t}) + \frac{L}{R} \tag{11}$$

in which

$$\beta = \frac{S\,(L+P)}{2kL}$$

$$\alpha = \frac{S}{2kL}\,[\,4kL - (L+P)^2\,]^{-1/2}$$

and A and B are constants of integration.

It may be seen that the solution is a damped periodic function so long as α is real, corresponding to "hunting" in the servosystem. When α vanishes or becomes imaginary, the system's approach to a steady state is critically damped and overdamped, respectively.

In terms of system parameters, the conditon for critical damping may be seen to be $4kL = (L + P)^2$, and overdamping to be $(L + P)^2 > 4kL$.

The solution of Eq. 10 was obtained assuming R constant. However, for small rates of change in R one would nevertheless expect that the dynamic characteristics are determined entirely by the fixed system parameters of the vehicle. Its approach to a steady state would then possess similar characteristics, whether the final state is a straight path ($R \rightarrow \infty$) with $\sin\varphi$ decaying to zero, or whether the vehicle has entered into curve and $\sin\varphi$ exponentially approaches its steady-state value of L/R.

Analysis of the signal induced in the speed detector coil is essentially similar to the foregoing guidance detector analysis, with the exception that the y position coordinate replaces x in the position-dependent expressions, corresponding to the perpendicular relationship of the speed and guidance detector coils. Thus, the signal in the speed detector vanishes when the coil is in a position of longitudinal symmetry with respect to the control lane loops, showing a 180° phase shift on crossing these points of symmetry. Because there are two points of symmetry for each loop the frequency of detected signal, ν, in cycles per second is related simply to the speed, S, of the vehicle in miles per hour by $\nu = 1.47\ (S/2b)$ where b is given in feet.

ANALYSIS

In the foregoing section some general aspects of a new system for guidance and speed control of highway vehicles have been presented. Some analysis concerned with the functioning of this system has been developed. This analysis must be regarded as preliminary in that simplifications and assumptions have been made where deemed reasonable. In any contemplated engineering development, more detailed analysis must be made in conjunction with the acquisition of experimentally measured parameters. Nonetheless, the analysis indicates a firm theoretical foundation for the system operation and points to a number of theoretical advantages.

A major advantage derives from the situation that the system depends primarily on the phase of an error signal rather than its amplitude. This fact, coupled with a sufficiently high gain amplifier so that the system becomes null seeking, eliminates most of the sources of unreliability associated with amplitude detectors. More specifically, the system response is unaffected by drift in tuned circuits, variations in oscillator output, changes in control lane conditions, or a variety of factors that may affect the amplitude of any detected signal. Further details on the electronics involved need not be set forth here, because rather conventional circuitry and operation is envisioned. Needless to say, the amplifiers and phase detectors for both guidance control and speed control functions may be identical. If fabricated as modular units, considerable reduction of cost and simplification of maintenance and repair would be realized.

In regard to the electromechanical portion of a guidance control system, it would appear that this could be simply achieved through an electrically operated valve added to a conventional hydraulically powered steering mechanism. This may be done so as to allow easy manual override of the automatic system, yet also provide sufficient resistance to give the operator a sense of being "locked" to the guidance lane. With proper design, little or no override would be allowed from extraneous forces applied directly to the front wheels tending to alter their direction. These are important factors contributing to the over-all safety of the operation of any automatic guidance.

The electromechanical linkage in the speed control function may likewise be conceived to operate through an electrically controlled valve. In this case a vacuum-powered system derived from the intake manifold provides an inherent limit to the degree of acceleration possible.

It is apparent from the dynamic analysis of the system that the manner of linking the guidance control detector to the front wheel position has introduced an important proportional control factor, necessary for stable function of the guidance control. Without such proportional control, small deviations of the vehicle from the guidance lane or even irregularities in the lane itself would lead to rapid corrective responses resulting in excessive lateral acceleration. On the other hand, with proper choice of system parameters, critical damping of the vehicle response may be ensured.

The rapid decrease of signal strength with vertical distance shown in Figure 5 is an important factor in eliminating "noise" arising from spurious magnetic fields due to highway reinforcing. Furthermore, the broad response curve with high signal level resulting from relatively close spacing between the guidance assembly and guidance lane loops offers a desirable safety factor against possible "escape" from the control lane. Because the system is powered by vehicle equipment rather than depending on roadside power facilities, only low power levels need be employed, thus virtually eliminating extraneous radiation. In addition, problems of standing wave formation inherent in systems requiring transmission of rf along guidance lanes are avoided.

Certain safety features in addition to those dependent on the inherent reliability of the system and those specifically mentioned are undoubtedly desirable. The speed control function should be readily inactivated by either manual acceleration or braking. Also, this function should be instantaneously inactivated in case of loss of signal.

Such a loss of signal may likewise be indicated by audible and visual warning devices.

Finally, additions to this basic system may be easily superimposed to provide further control of vehicle operation. For instance, the vehicle speed may be automatically reduced in zones of recurrent or permanent danger by a reduction in loop size. Speed modulation may be temporarily imposed in other zones by low-level transmission of rf pulses along the guidance lane conductors. Such pulses could originate from an externally coupled generator borne by patrol vehicles and are easily summed to those arising from guidance lane loops to provide the modulation desired.

A variety of schemes pursuant to the detection of lane obstruction by other vehicles, overtaking of other vehicles, automatic braking, decision functions at highway intersections, and traffic pattern control may be desired in any future elaboration. For the present, however, the low cost of installation and maintenance of passive highway elements and the individualized nature of control functions offer great advantage for possibilities of immediate implementation of guidance and speed control followed by a gradual public adoption through use.

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