Development of an Electronic Highway Aid System

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• FREEWAYS are presently receiving considerable attention because of the large volumes of traffic they carry in urban complexes. Another major phase of U.S. traffic is that of suburban and rural two- and three-lane arteries and highways. Even though the traffic density may be high on latter routes, considerations (such as expected traffic volume, acreage available, large numbers of necessary accesses, and cost) rule out their replacement with freeways. Still, the accident rate and congestion on these routes indicate that something should certainly be done to improve their traffic flow and safety. The solution of this problem is directly applicable to the freeways as they become saturated.

Utilization of electronic devices as traffic aids has been suggested to improve traffic conditions. Fundamental research is presently being conducted to determine how electronics may best be used and the feasibility of this use. This paper attempts to describe this research and show how it leads to a traffic control system.

WARNING SYSTEM AS INTERMEDIATE OBJECTIVE

The completely automatic driving system, including automatic steering and automatic acceleration and braking, is drawing the attention of a number of engineers. The potential improvement in traffic flow and safety of such a system is indeed lucrative. However, if the driver's individual freedom is to be preserved, the dynamic problems to be solved en route to such a system are many and complex.

Furthermore, the transition from manual to automatic driving must be acceptable to a rather skeptical public. Perhaps the most convenient way of making it acceptable is to go through a warning system phase in which the driver retains complete control of the automobile, but has auxiliary sensing and decision-making equipment that will indicate the existence of a potentially dangerous situation. It can provide the driver with ability he does not now have, such as blind passing, lane changing, and sensing traffic on blind approaches. These extra senses can improve the flow of traffic as the drivers begin to rely on the system. However, it is anticipated that three other goals will be realized with the warning system:

1. Increasing safety.
2. Acquainting the public with the electronic system and its capability and developing their confidence in it.
3. Giving the engineers a chance to test and develop reliability in the fundamental system components (the detectors, logic circuitry, power distribution, etc.) that will be used in the automatic system.

Once this is accomplished, the automatic system will be completed by a mechanization of the automobile—a step already being explored by the automobile industry. (It is anticipated that the equipment within the highway for the warning system will be identical to that for the fully automatic system.)

Experience gained in man's work with automatic machines indicates that for some time to come it will be necessary to use the man's continuous supervision. The best way to do this is to give him part of the task of driving, to keep his attention on the road. Also, this is necessary inasmuch as it will be some time before sensors will detect such objects as people, animals, boxes, etc. Driving in general has two degrees of freedom—lateral (steering) and logitudinal (acceleration and braking). Automatic acceleration and braking offers more gains in traffic density and in preventing rear end collisions, so the task chosen for the man is steering. For this reason the research is being concentrated on acceleration and braking. An investigation of steering techniques (1) is being made at this time.

HUMAN DRIVER CHARACTERISTICS

Design of a warning system is directly dependent on human driving characteristics, (2) because the warning system must not lead the driver into dangerous situations he cannot get out of, nor must it be too conservative. If the warning is too late, the system will be feared, whereas if it is too early, it may be ignored; therefore the system must be matched to the driver. This requires determination of the criteria according to which the driver accelerates and decelerates his car. It should be in the form of a mathematical expression with numerical constants.

The literature contains a number of analyses (3, 4, 5) attempting to arrive at the driving criteria. Most of these have been based on measurements of traffic quantities such as traffic flow. Inferences were then made to arrive at expressions for acceleration and deceleration criteria.

Another approach being taken is based on measurements of variables involving 2 vehicles, such as headway and relative velocity. It also considers a number of observations from experience, of driving modes as well as analytical treatment of senses, such as depth perception. To facilitate this work an automobile simulator was constructed to simulate the two-car problem. This simulator is such that the mathematical expressions and the human driver can be tested in it and compared directly. Also, the measurements of headway and relative velocity are easily obtained from it.

Analytical examination of the equations available in the literature showed that none of these were sufficient as they were presented to describe the driver in the car-following problem. One of the most promising of these (also the most widely accepted),

$$a_{2_\tau} = k \frac{v_1 - v_2}{h} \tag{1}$$

in which

a_2 = acceleration of the following car with a lag of τ seconds in the driver's response;
v_1 = velocity of the lead car;
v_2 = velocity of the following car;
h = distance between the cars; and
k = sensitivity constant in units of velocity

was studied on the analog computer. It was found that the steady state headway existing when $v_1 - v_2 = 0$ is a function of the initial headway h_0 and relative velocity $v_0 = v_{1_0} - v_{2_0}$. The computer study also indicated that by proper choice of initial conditions the steady state headway could be controlled. Curves recorded on the analog computer simulator which show the similarity of the human response and the response governed by Eq. 1 are shown in Figures 1 and 2. The solution of Eq. 1 is a reasonable approximation to actual response, for the region where $v_1 - v_2 < 0$. In the region where $v_1 - v_2 \cong 0$ the solution of this equation does not contain oscillations about an average headway, which is a characteristic of the human driver. (The curves in these figures are called phase trajectories. Time has been eliminated on the plots in plotting relative velocity $v_1 - v_2$ as a function of headway h. The change of state with increasing time is in the direction of the arrows.)

A number of other equations were studied that might have a fundamental physical basis or which were a summation of terms chosen to describe the response of the human driver. These equations are given in Table 1 with their inherent shortcomings.

The consideration of the driver as a multimode device means that some terms of the driving equation will apply for some values of the variables, $v_1 - v_2$ and h, and not

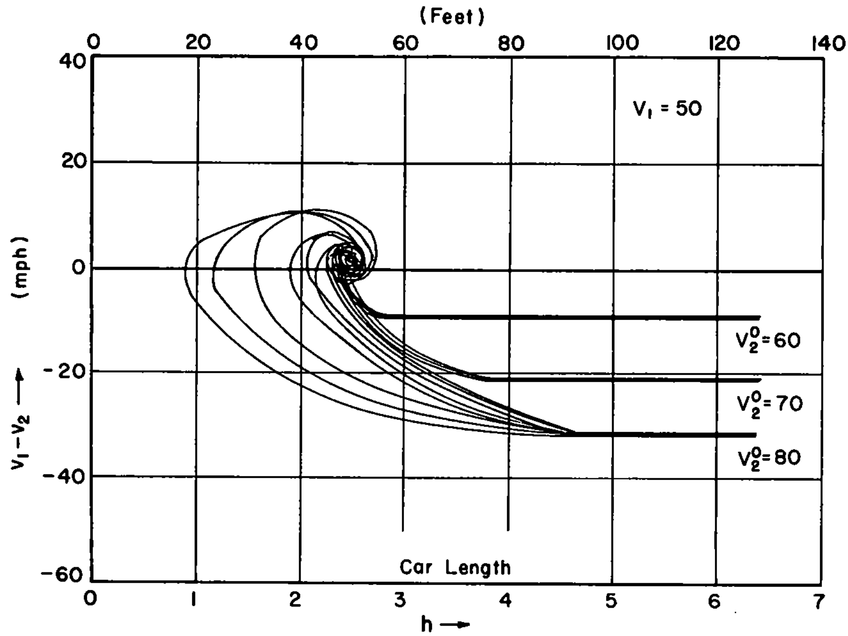

Figure 1. Phase trajectories of human driver overtaking lead car in automobile simulator.

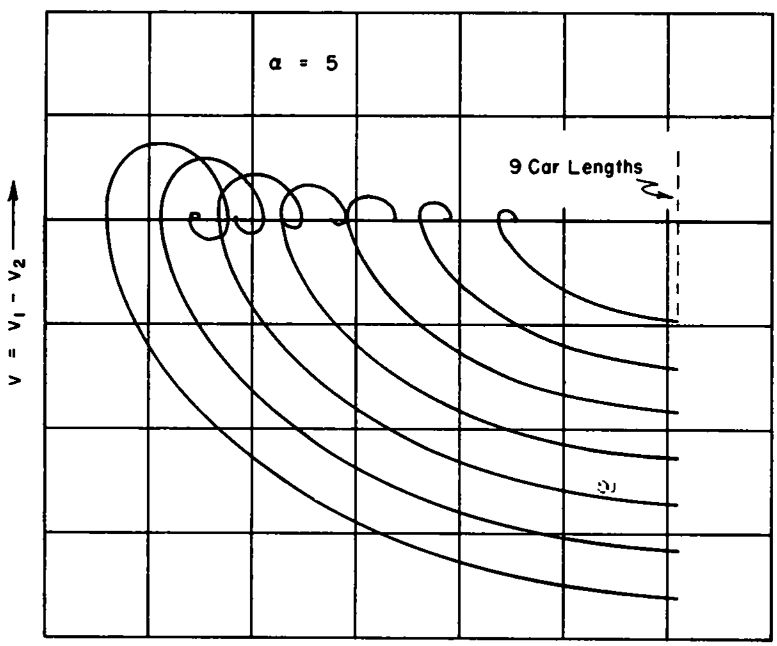

Figure 2. Analog computer solution of $a_{a_T} = \alpha \frac{v}{h}$.

TABLE 1

Equation No.	Equation Form	Type	Comment
1	$a_{2_T} = \alpha \frac{v}{h}$	Sensorial	No distance criterion
2	$a_{2_T} = \alpha \frac{v}{h} u\ [F - h]$	Proper initial conditions added to Eq. 1 to provide the distance criterion	Model under study
3	$a_2 = \alpha \frac{v}{h} + (h - H)$	Simple distance criterion added to Eq. 1	$\lim a_2 = \infty \quad h \to \infty$ also, same as No. 5
4	$a_2 = \alpha \frac{v}{h} + K \frac{h-H}{h}$	Simple sensorial distance term added to Eq. 1	$\lim a_2 = K \quad h \to \infty$ also, same as No. 5
5	$a_2 = \alpha \frac{v}{h} + K \frac{h - H}{h^2}$	Sensorial distance term added to Eq. 1	Tendency of following car to accelerate before decelerating when in vicinity of lead car
6	$a_2 = \frac{\alpha_v + k (h - H)}{h^3}$	Based on possible subconscious judgment of driver	Same as No. 5
7	a_2 = constant = function of initial vel. and headway (tri-mode type)	Based on possible subconscious judgment of driver	Model under study

apply to other values. Although this seems to be the most promising area of thought at present, it does not uniquely specify the actual driving criteria, inasmuch as many different equations may be matched to any one human driver response. The fact that this looks so promising indicates that either the human driver is actually a multimode device, or that a true physically justifiable description of the driver has not been found.

So far, for large $v_1 - v_2$, Eq. 1 seems to be the most physically justifiable and similar in solution to human driver response. For small $v_1 - v_2$, indications are that the driver is quite nonlinear, and the description of the nonlinearity is not complete at this time. However, it is important to the system stability analysis that must be performed in the near future.

INSTRUMENT DRIVING

The process of a human driver responding to instruments in the automobile, instead of to his visual sense is a relatively new one. It requires some thought in the area of the development of ground rules for the guidance of work in this field.

If a driver were to drive blind, he would be able to sense only the inertia forces on his body and the back pressure on the foot pedals. Given a warning signal with only

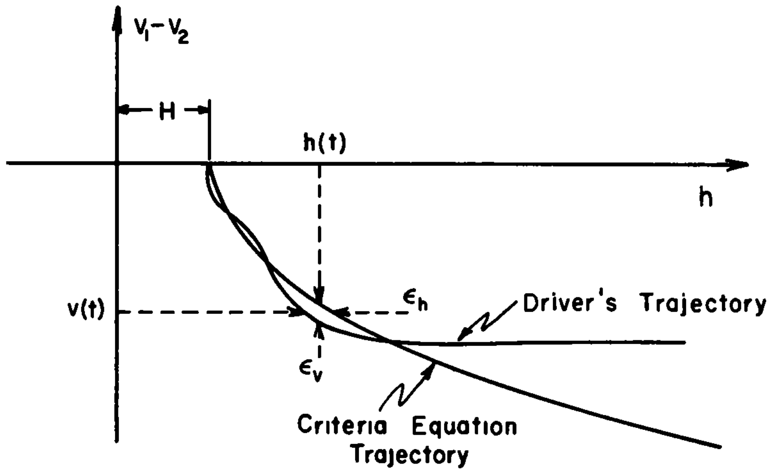

Figure 3. Comparison of driver's response with criteria.

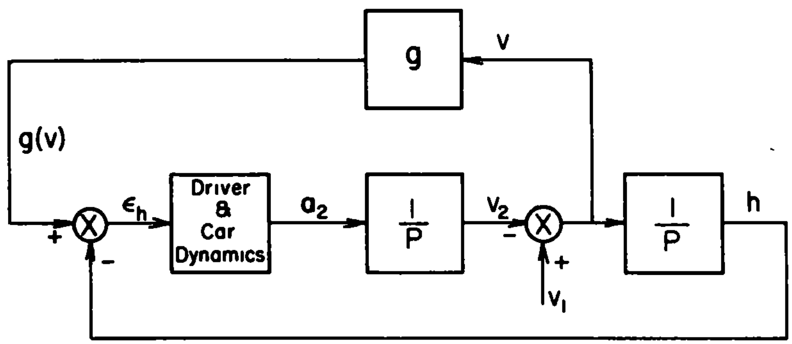

Figure 4. Continuous system with driver correcting headway error.

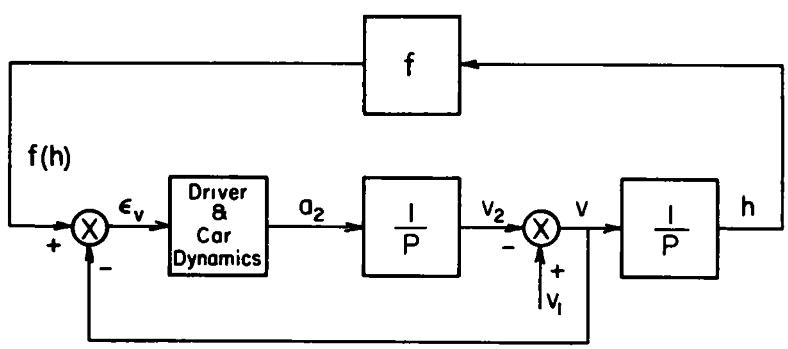

Figure 5. Continuous system with driver correcting velocity error.

that much information, it is reasonable to expect him to pick out a deceleration level and maintain it constant. If his resultant deceleration were great enough, he could avoid a collision. However, if it was not, he would collide. It becomes apparent that he must not only sense a warning, but also the degree of the warning.

A further restriction is that he still must keep his eye on the road for steering. This requires the warning to be either audio or located in the driver's peripheral vision.

Further, it would be desirable to control the driver's deceleration in such a way that it was similar to that of his visual response, so that his deceleration would feel natural to him.

These requirements can be combined to the realization of a system through a consideration of phase trajectories. A phase trajectory is merely a special plot of the solution of a second order differential equation together with its initial conditions. These solutions are unique to the equations. The technique being used in the design of the warning system is to select the driving criteria equation that most nearly represents the driver under normal driving conditions. A warning light is then actuated so that it displays the difference, ϵ_h, between the actual headway and that computed from the criteria equation $h = g(v)$ for the existing instantaneous actual relative velocity, $v(t)$, as shown in Figure 3. Also, the driving criteria trajectory may be written $v = f(h)$. If the warning light were now actuated to display ϵ_v, the driver would be correcting the velocity error for the instantaneous headway. This defines the two systems shown in Figures 4 and 5. It is the driving criteria that determine the $f(h)$ or the $g(v)$. The system design problem is then the implementation of the $f(h)$ or $g(v)$, the comparison of this function with measured v_1, v_2, and h, and the delivery of the error signal from the highway to the driver.

There are several different criteria that might be used for $h = g(v)$. Their trajectories are shown in Figure 6.

The linear trajectory and the exponential trajectory do not cross the $v = 0$ axis perpendicularly; that is,

$$\left.\frac{dh}{dv}\right|_{v=0} \neq 0.$$

Now,

$$v = \frac{dh}{dt}$$

$$= \frac{dh}{dv}\ \frac{dv}{dt} = a\,\frac{dh}{dv}$$

$$\frac{dh}{dv} = \frac{v}{a}$$

$$\left.\frac{dh}{dv}\right|_{v=0} = 0 \text{ unless } a \rightarrow 0 \text{ as } v \rightarrow 0.$$

This means that as the relative velocity approaches zero, the driver will be gradually reducing the braking force and taking a very long time to reach the steady state, if he maintains zero headway error; i.e., if $\epsilon_h = 0$, so that he follows the trajectory exactly.

THE HIGHWAY SYSTEM

The highway system has three major functional components: (a) the sensors, which detect the presence of an automobile; (b) the logic circuitry, which makes calculations of headway error based on the outputs of the detectors; and (c) an induction transmitter which broadcasts the headway error signal (warning signal) to the automobile. The automobile will need an induction radio receiver to receive the error signal and operate a warning light or buzzer. However, this is not discussed here, except to

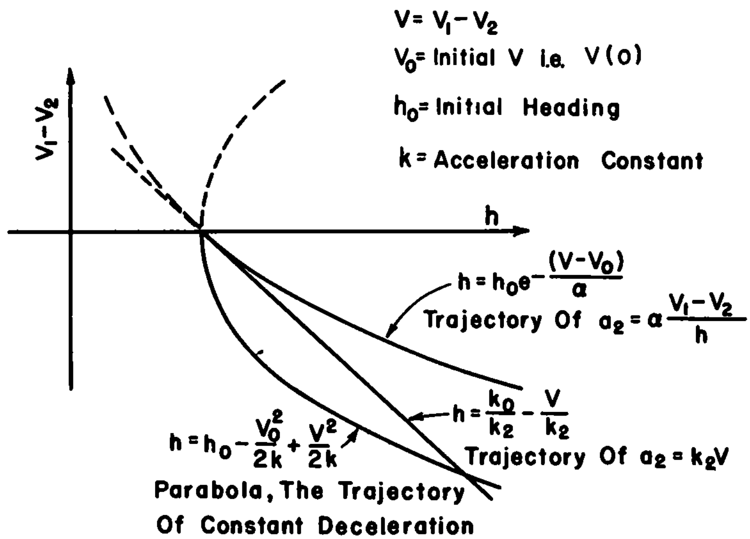

Figure 6. Possible g(h) functions.

mention that these are already available (for instance, Hy-Com by General Motors).

The sensors envisioned at present are rectangular magnetic loops buried in the highway as shown in Figure 7.

The loops are actuated by alternating current source. When an automobile passes over the loop, it changes the loop's electrical characteristic, so that it upsets a phase balance. This is detected, and relay contacts are closed when the car is in the loop. Such loops are currently available, and they have been successfully installed in airports, where they detected airplanes.

The logic circuitry being considered at present does not calculate exactly any of the criteria previously described. It most nearly approximates the linear criteria shown in Figure 6; namely,

$$h = k_1 - k_2 v$$

or

$$h = k_1 - k_2 v_1 + k_2 v_2$$

This was chosen for implementation because it appears to be the simplest criteria to implement. How this linear function is generated is described after a consideration of the basic elements of logic circuitry and the circuitry proposed at this time.

Before describing the details of logic circuitry, the nature of the symbolism is briefly reviewed. Four elements will be used in the diagrams, namely " and" units designated by an encircled "A," "or" units by an encircled "O," flip-flops and delay flip-flops.

Input signals to an element are represented as signals following paths with arrow heads pointing into the element. The output signal exists on a path or paths with arrow heads pointing away from the element. The "or" unit will produce an output signal (often termed an "on" signal) when any one or more of the input signals are "on" (see Fig. 8a). Here the input signals are x_1, x_2, and x_3, and the output is designated by y_1.

The "and" unit has two or more input signals and one output signal. The output signal is in the "on" state if and only if all the input signals are "on." The flip-flop is a bi-stable element, sometimes called a toggle element (see Fig. 8b). It has two input terminals and two corresponding output terminals. If the input to the "one" side of the flip-flop x_1 is excited with an "on" signal, the output signal of the "one" side will be turned on and remain on regardless of variations of x_1 until x_0 is turned on. Once x_0

is turned on, "y_1" is turned off and "y_0" on. The flip-flop is said to be in the "on" state when the output signal from the "1" side (namely, x_1) is in the "on" state.

The delay flip-flop is generally interconnected so that only the "one" side is excited (signal x_1 of Fig. 8b). This input signal is generally a short pulse and y_1 will remain on while the input signal is on and for a fixed period T after x_1 is turned off. Thus y_0 will normally be on except for the period T after x_1 is turned off.

Figure 9 is a diagram of a logic circuit that will activate a zone with the number of blocks activated equal to T_1/T_2 where T_1 is the period the vehicle remains within a block and T_2 is the delay time of each delay flip-flop.

This circuit is rather complex and, as such, the elements of each basic operation is discussed. When a vehicle moves into a block, (for example block 1), the flip-flops in blocks 2, 3, 4, and 5 will be turned on in sequence, block 3 T_2 seconds after block 2, etc. The delay is accomplished by the delay flip-flops. When the delay flip-flop returns to the zero state, the output from the zero side of the flip-flop is formed into a pulse by the units marked f. Thus a vehicle moving into block 2 will cause the delay flip-flop in block 3 to be activated. T_2 second later the zero side of this flip-flop will be activated causing the delay flip-flop in block 4 to be turned on. T_2 seconds later delay flip-flop in block 5 will be turned on.

In essence a vehicle moving into a new block will cause a zone of "on" transmitters to move to the rear of the vehicle. If this sequence is to start anew each time the vehicle moves into a new block, it is necessary that all flip-flops be reset. This resetting process is accomplished by the row of circuits labeled and-or combination. Assuming that flip-flops in blocks 3, 4, and 5 are on, the automobile moves into block

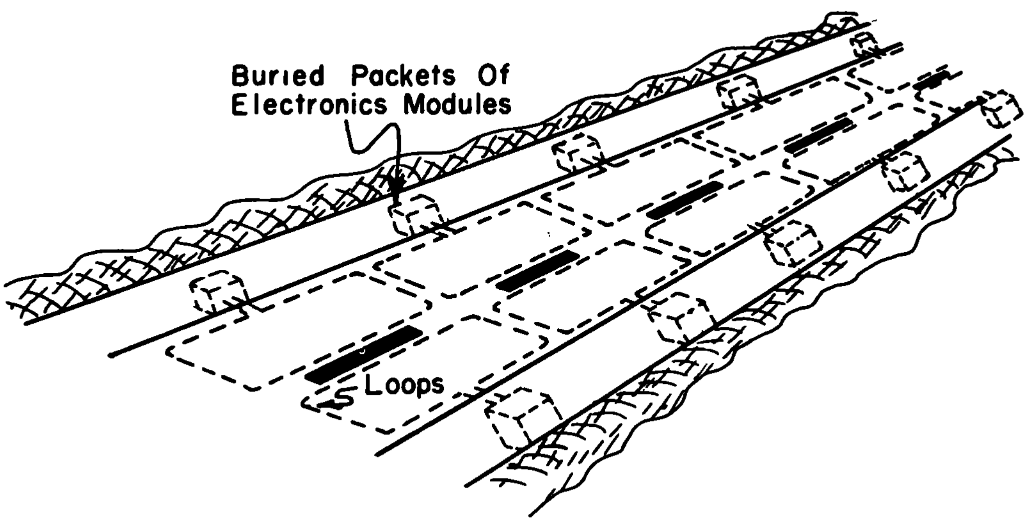

Figure 7. Physical highway layout.

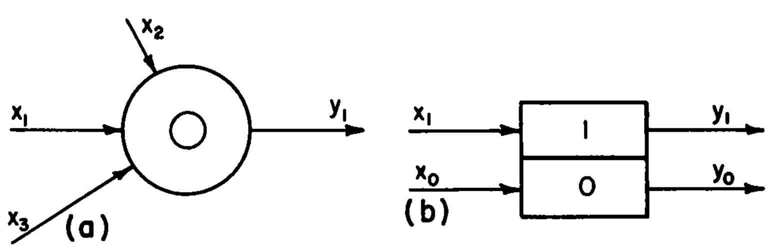

Figure 8. (a) "OR" circuit; (b) "Flip-flop" circuit.

1. The x_1-signal, a pulse, passes through the "or" circuit to the "and" unit in block 2. The output signal from this "and" unit turns off the flip-flop in block 3 and also this signal passes through the "or" unit to the next "and" unit both in block 3 with little delay. The output from this latter "and" unit turns off flip-flop in block 4, etc. In essence, all activated flip-flops are turned to the "off" state almost instantaneously once the vehicle moves into a new block. This operation is termed a resetting operation.

There is one further interconnection of the blocks. Each time a block is turned on, it activates a block N blocks forward from it (in the direction the automobile is traveling). This fixes the total zone of the automobile at N block lengths.

Now it was indicated that the zone extends behind the automobile a distance

$$\frac{T_1}{T_2} l_b = \text{length of "tail zone"}$$

in which

l_b = length of a block-constant;

T_2 = delay time of the delay flip-flops (a constant); and

T_1 = time the car is in the block so that

$$T_1 = \frac{l_b}{v_1}$$

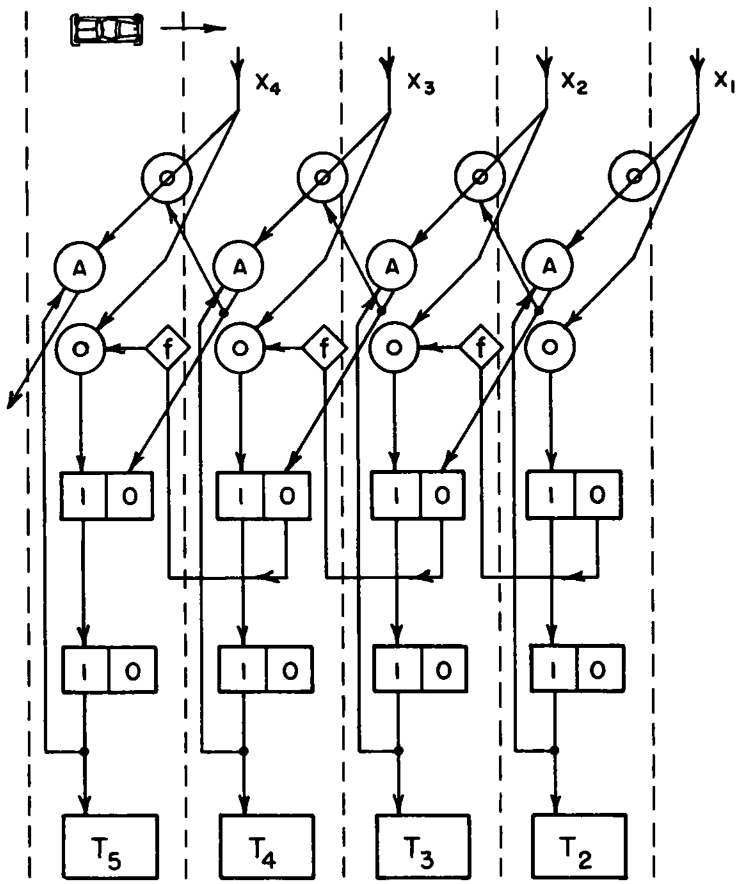

Figure 9. Highway logic circuitry.

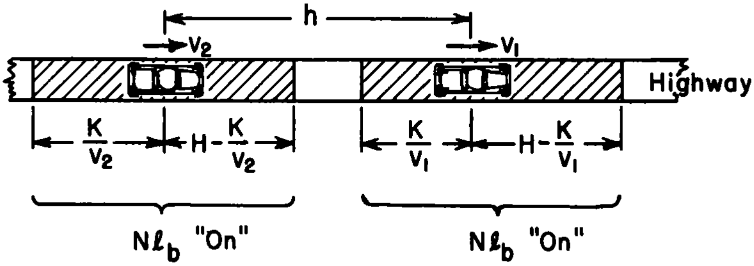

Figure 10. Zones of two cars.

Thus the "tail zone" length is $\frac{K}{v_1}$ where v_1 is velocity of the car. Because the total length of the zone is fixed,

$$\text{"head zone" length} = Nl_b - \frac{K}{v_1}$$

$$= H - \frac{K}{v_1} \text{ (H constant).}$$

This is shown for two cars in Figure 10.

When the zones overlap, the distance of overlap will be $H - \frac{K}{v_1} + \frac{K}{v_1} - h$ (headway error, ϵ_h), in which h is actual headway. Whereas, what is desired is

$$\epsilon_h = k_1 - k_2 v_1 + k_2 v_2 - h.$$

Now if the length K/v_1 is plotted against v_1, it is an hyperbola as shown in Figure 11. Figure 11 shows that K/v_1 may be a reasonable approximation to $k_1 - k_2 v_1$ in the range of velocities $V_1 < v_1 < V_2$. Similarly, $k_2 v_2$ may be approximated by $H - \frac{K}{v_2}$ in the range $V_1 < v_2 < V_2$ (see Fig. 12), so that if the driver decelerates proportional to

$$\epsilon_h = H - \frac{K}{v_2} + \frac{K}{v_1} - h$$

he will be approximating

$$\epsilon_h = k_1 - k_2 v_1 + k_2 v_2 - h.$$

Thus if he keeps ϵ_h small, he will be following the linear trajectory of Figure 6 in the rapid approach problem.

The headway error, ϵ_h, is measured by more logic which determines blocks that are actuated both as head zones and as tail zones. This indicates the use of "and" circuits as shown in Figure 13. The number of overlaps indicates the degree of warning transmitted to the block of the automobile.

Finally an induction radio transmitter in the following car's block is turned on with an intensity proportional to the degree of overlap. Biasing the system allows one to operate a red and a green light in the driver's peripheral vision as shown in Figure 14.

Tests with human drivers driving by

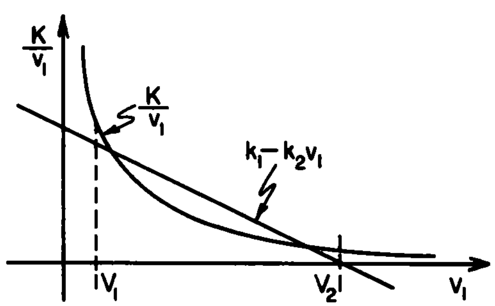

Figure 11. Approximation of $k_1 - k_2 v_1$ with $\frac{k}{v_1}$.

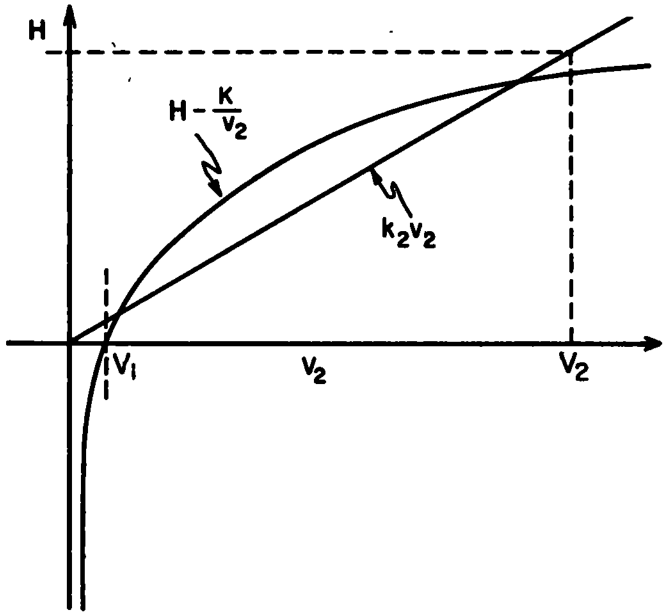

Figure 12 Approximation of $k_2 v_2$ by $H - \frac{k}{v_1}$.

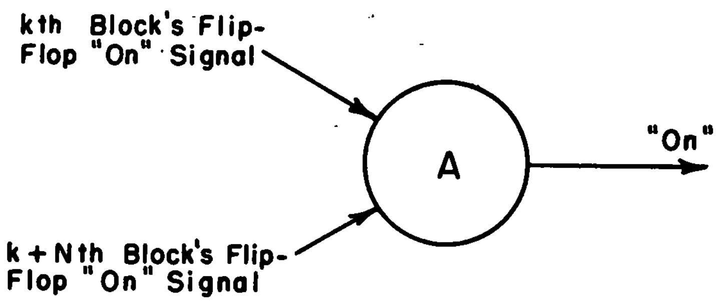

Figure 13. k^{th} block's "and" warning circuit.

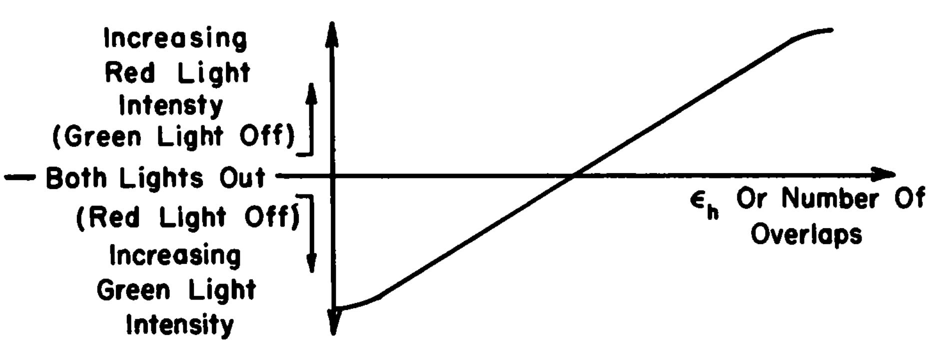

Figure 14. Warning vs overlap.

the lights in an analog computer simulation in the laboratory have indicated that the driver can maintain a headway, k_1, better than he can by seeing the lead car.

SUMMARY

This paper summarizes the work done by the Ohio State University Antenna Laboratory under the sponsorship of the U.S. Bureau of Public Roads and the Ohio Department of Highways. Briefly, a study is made of the human driver to determine his normal visual response. Then his function in an electronic warning system is determined. The system computation is specified by the driver's normal visual driving criteria. Finally, such a system is implemented. Much research and engineering remains to be done, before such a system can be installed, but the indications of feasibility and performance of the venture are optimistic.

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