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Contents

Detection and Location of Off-the-Shoulder Vehicles

R.L. COSGRIFF and R.B. LACKEY, Antenna Laboratory, Department of Electrical Engineering, Ohio State University

• THE MODERN Interstate highway is truly a boon to the motorist. By using these highways, he will ultimately be able to drive between most major cities without red lights, stop signs, intersections, school zones, or five o'clock rush hours. In short, driving will be smooth sailing. Smooth, that is, if his car doesn't stop running for one reason or another. Statistics probably show that the average motorist will have one breakdown (mechanical or otherwise) for each x miles of freeway driving. No one pays much attention to these figures until he becomes part of them. Because the Federal government has ruled that there will be no service stations on any new Interstate highway, the stranded motorist is faced with a dilemma. In short, he is at the mercy of time, space, white handkerchiefs, and passing motorists. How to help this unfortunate driver is but one part of the highway research program being conducted at the Antenna Laboratory, Department of Electrical Engineering, Ohio State University.

GUIDED EVOLUTION

An over-all philosophy for the design and implementation of electronics for the highway has been developed. This philosphy is called "Guided Evolution," and may be described as follows: Ultimate goals for the ideal electronic highway have been set, and steps for accomplishing these goals have been outlined. Guided evolution requires that each new development, each new device, be an integral part of this long-range plan and compatible with the ultimate goal. The purpose of guided evolution is to prevent successive installation and removal of isolated gadgets that, although they may provide temporary solutions to a part of the problem, do not appear in the final picture. Ultimately, the location of an off-the-shoulder vehicle will be relayed to a central station automatically, requiring no action whatsoever by the motorist. This goal, however, is probably not realizable in the next several years. On the other hand, the problem is serious enough that an immediate step should be taken to aid the stranded motorist and yet maintain compatibility with the guided evolution goals.

INTERIM SOLUTIONS

Several interim solutions are available for the stranded motorist problem. Some of these will only detect the presence of an off-the-shoulder vehicle, whereas others locate him as well. Those serving only to detect will not be discussed inasmuch as detection without location serves practically no useful purpose. Of the systems that locate an off-the-shoulder vehicle, some require action by the motorist and others do not. These systems are discussed according to this classification.

The following are systems requiring driver action: A telephone system, either conventional or sound-powered, could be installed along the highway. This in effect would set up a communication network between the driver and a central location, and the exact nature of the motorist's difficulty could be transmitted. Another type of system complete with solar batteries and digital encoders has been developed by Hoffman Electronics. In this system, the motorist merely pushes a button on a call-box (located at ½-mi intervals) and signals his location and the nature of his difficulty to a central station. North Electric Company in Ohio has a system that, although it was designed primarily for setting and adjusting road signs from a remote location, can incorporate telephone circuits to aid the stranded motorist. This system also has a protection feature whereby a signal is received if a telephone is disconnected. This might at least retard vandalism to some extent. Finally, an effective interim solution would be the application of a technique long used by power companies in locating short circuits in power lines; that is, the measurement of resistance. The installation of a system of this type requires the following steps: burying a cable along both sides of the highway to be instrumented; placing switches at ½-mi intervals along this cable which can short-circuit the cable; placing resistance-measuring equipment including a bridge circuit, a power supply, a digital voltmeter, and an alarm in a central station. Thus, when the motorist throws the nearest shorting switch, an alarm in the central station announces that a motorist is stranded, and the digital voltmeter gives a numerical indication of the location of the motorist. A further refinement, which could be installed at nominal cost, is an indicator light mounted near the shorting switch. This would come on when the signal is sent by the motorist, and be reset from the central location when help is dispatched. Thus the motorist knows when his distress signal has been received.

Systems requiring no driver action have one feature in common: the only requirement for their operation is that a vehicle be driven off the shoulder of the highway. Thus, in considering possible approaches, one needs only to list various methods whereby the presence of a vehicle may be detected (with a time delay, of course, to eliminate false alarm signals from vehicles that leave the highway temporarily and return). Any detector, therefore, whether magnetic, electronic, infrared, mechanical, or other, may serve as the basis for this type of system. The outstanding feature of all of these is that no action by the driver is required. This technique is in strict accord with the principles of guided evolution, and will eventually be used. For the present, however, a system of this type is not feasible because it is only an efficient method if used as part of the ultimate electronic highway. This is due to the nature of the over-all system and to the condition that if parts of the system were to be installed separately, there would necessarily be duplication of many components.

Based on the foregoing reasoning, only the systems requiring driver action are compared. The installation of a telephone network between the highway and a central station would be an excellent solution to the stranded motorist problem except for one major drawback. The presence of telephone equipment on the highway is an open invitation to vandalism and it is well known that the loss of such equipment is relatively high. The Hoffman System, or one comparable to it, has as its main drawback its high installation cost. It is felt that because of this, it is too costly to be used as an interim measure. Furthermore, it is not compatible with guided evolution because it requires action by the motorist. Finally, although the resistance-measuring system is not thought of as a final solution, its cost of installation makes it very appealing as an interim measure. Moreover, it requires no expensive components (such as telephones) in remote locations. If a more precise communication is desired, it would be relatively easy to devise a code whereby the motorist could "talk" to the monitor in the central location. Finally, pertaining to the guided evolution concept, the cable itself could ultimately be used to deliver power to the electronic circuitry required in the final version of the electronic highway.

SUMMARY AND CONCLUSIONS

Of all the systems discussed as possible temporary solutions to the problem of the stranded motorist, the technique involving resistance measurements appears to be most satisfactory. The reasons for this conclusion are as follows: It has no expensive components (such as telephones or solar batteries) that may be stolen. It has a relatively low initial cost as compared with an elaborate digital system. Finally, the resistance-measuring technique gives the motorist a signal that help is on the way, as well as allowing him to specify (in code) the nature of his difficulty. On realization of the ultimate electronic highway, according to the principles of guided evolution, the buried cable can be utilized in the delivery of power to the electronic circuits.

ACKNOWLEDGMENTS

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Comments on an Electronic Highway–Some Specific Techniques and Suggestions for a Test Roadway

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The potential applications of electronic techniques and devices to highway uses have been investigated by RCA and other workers in electronic research and development for a number of years. It is now appropriate to bring closer together the two disciplines of electronic and highway engineering so that maximum use may be realized at an early date and with a minimum of expenditure. This paper describes some of the factors involved in a cooperative endeavor, some specific techniques used by RCA in its "system approach" to an electronic highway, and a suggestion for a cooperative project on public highways.

• FOR MANY YEARS the subject of automatic control of highway vehicles has been discussed at meetings of associations active in the highway field. RCA, through its research activities, has been studying for about 10 years possible applications of familiar techniques that might be applied to solving some of the needs of highway travel.

Specific developments and tests that have been conducted have already been reported. Therefore, with a background of information now available, and with the progress that has been made in techniques and system considerations, it is time to initiate a full-scale test with participation by highway authorities toward a truly objective evaluation of short-range and long-range potentials.

The situation at this time is similar to that which existed in other fields prior to major advances. Many isolated facts are available, a general realization of the needs are visualized, numerous individual factions are interested in and have worked in the specific fields, and yet there has been no over-all agency pulling together in an effective manner this available information.

This paper attempts to put into perspective the needs, some possible solutions, and the "state of the art" that would permit adopting these solutions. Such review might aid in establishing a practical program for a single agency to provide the necessary leadership in pulling together the available information and considering it in proper context. In the language of the electronics industry, it is proposed to consider the over-all system, rather than separate parts.

The needs, can be summed up in four categories within which there are other individual components:

1. The need for increased safety.
2. The need to reduce total highway expenditures per vehicle-mile of travel.
3. The need to reduce travel time.
4. The need to reduce the effort required to drive a highway vehicle.

No differentiation is made in degree of importance and, furthermore, improvement in any of these areas would be progress.

Recent developments in many technical fields are applicable to highway usage and this is particularly true of electronics. This field has produced many devices for control, navigation, and communication purposes that with modification could provide assistance in vehicle transportation. The work of RCA, and others, has been concerned primarily with the solution of technical problems. The application of electronic devices originally developed for both military and commercial applications may not be economically justified in some instances without major redesign of the equipment because of the high cost of the product and the amount of maintenance required. Experimentation to date has indicated, however, that many of these techniques may be applied to the construction of highway aids at a cost that would not be prohibitive and yet would provide the degree of reliability required. RCA's work, which has been primarily of a research nature, has studied many individual traffic aids that have been suggested by persons within RCA and outside RCA, and have attempted to visualize the long-range acceptance of these individual aids into a system that could grow by adding features with little or no premature obsolesence of previously adopted devices. RCA has taken the approach that complete control of the vehicle on a highway would be the ideal toward which to strive. Therefore, it has built and demonstrated the operation of full-size vehicles on the test track at its laboratories in Princeton, N.J. This track is equipped with devices permitting complete control of suitably equipped vehicles on a single lane of highway, even in the presence of the usual operator-controlled vehicles running in the same lane. In its simplest form, complete control of vehicles requires the performance of only two basic functions: (a) the vehicle must be maintained in its lane (i.e., provided with guidance) and (b) a means must be provided to maintain a proper spacing behind the vehicle preceding it in the same lane of traffic. These functions are built into the test roadway. The equipped automobile has pickup coils and suitable electronic equipment to provide an electrical signal to operate the car's power steering. It also has electronic equipment to pick up from wires in the roadway signals that measure the distance to and the speed of the car immediately ahead. This thereby provides a signal to permit adjustment of speed by operation of accelerator or brake to maintain proper spacing.

Though such complete control could be installed in any highway and in any vehicle today, the economic problems of justification and growth will not permit such a program to proceed rapidly because of the large standard-road mileage in existence today and the large number of cars not suitably equipped. However, highway authorities should establish a program to study such an ultimate system starting at the point currently reached by RCA and other laboratories.

Of greater practical value, however, for the immediate future is the identification of such a system's elements that could be adopted immediately with little or additional development. Such devices include methods of warning vehicles on portions of highway hidden from view because of blind curves or crests of hills. The application of detection devices developed for the automatic highway to purposes of traffic control at intersections would provide the ability to handle a higher volume of traffic at intersections by eliminating time needlessly used for the purpose of changing signals beyond that actually required for the amount of traffic at the intersection and its rate of movement.

Another application would provide a warning to drivers of vehicles traveling in fog that they were overtaking a slower-moving vehicle ahead that they could not see. Aids to vehicle operators such as those just described would require no equipment in the car. If, however, one is willing to consider the installation of electronic equipment in a car, it is possible to supplement the roadside warning techniques with in-car lights or buzzers actuated by the electronic equipment in the highway to provide an additional degree of warning to the vehicle operator. Such equipment would be similar to that providing the control signals for the fully automated vehicle. In other words, selection of a basically sound system would permit expansion into the fully automatic system on a gradual basis. Therefore, during the period of transition three types of vehicles could be operated in an intermixed manner: (a) standard vehicle (b) the vehicle having in-car warning equipment but not fully automated, and (c) the fully automated vehicle. If it is agreed that there is the need to provide improvements of these types, it appears desirable to consider the feasibility of application of an ultimate system permitting the use of interim devices that will provide the vehicle operator with a useful service immediately and would not be obsoleted when full control is eventually provided. Also, though work has been directed to the ultimate system, the immediate adoption of this or any other system of full automation is not proposed. However, it is considered in the public interest to initiate now a cooperative program of study and development that considers the ultimate system.

To be specific, RCA has proposed that a suitable project would consist of two lanes (one each way) of a four-lane highway for a length of 5 mi that would include electronic equipment providing complete control and a number of highway aids for fully equipped vehicles. This would provide 10 lane-mi of fully equipped highway. In addition, feeder roads that would by typical non-turnpike roadways should be equipped with warning devices at blind curves, over crests of hills, at intersections that have unique or serious traffic handling problems, at blind junctions where two roads merge into one, at entrances and exits or where roads lead to and from limited-access highways, and electronic-visual aids at locations of "two-level" merge.

Detection coils in the highway may be connected in a very simple manner to provide a measurement of speed. This signal may be used to flash on a warning sign that might read "Slow Down—You Are Exceeding the Speed Limit."

With no vehicle equipment other than the standard car radio, an oral signal could be provided that would permit advising the driver of conditions along the highway, especially in times of accident or disaster, and this could also be used on a localized basis to provide information on availability of food and lodging in the vicinity of that particular broadcast. With lights of a type similar to those used on airport landing strips buried in the center of the roadway lane, it would be possible to have a series of several lights precede a vehicle along the highway which would provide a guidance light during periods of poor visibility. At regular intervals, call boxes would permit a motorist with a disabled car to call for assistance.

A roadway of the type described could be partially equipped and initial testing begun in approximately one year from the date of authorization to proceed. A one-year test should permit elimination of operating bugs, demonstrations to interested parties, establishment of a number of standards, and the preparation of plans for application of some of these services to ordinary highways.

Selection of a test location should consider factors such as accessibility, weather, soil, surface material, width of lanes, number of lanes, fog conditions, volume of traffic, and convenience of availability for testing, including the ability to close at least one lane of traffic at certain times without completely disrupting the flow of traffic.

A cooperative program and test roadway would not only provide a laboratory for development but would also serve the necessary service of a demonstration location. One of the greatest difficulties in establishing a new product or service is to attempt to do so without a sample. A roadway equipped as described should permit the prospective State, local, and Federal highway personnel witness the performance of some of these technical devices and evaluate them in terms of their own possible usage. The electronics industry, because it lacks the intimate familiarity with highway problems, is not able to evaluate the relative worth of the various components of a system of the type described. Such a project as described will provide highway and electronic engineers with a much better knowledge of each other's field and thus produce an effective team of workers.

To equip a roadway in the manner described, considerable equipment will be required. In spite of this, however, the cost of such equipment will be a small portion of the cost of a roadway. It is for this reason that those in the electronics industry believe a cooperative project could develop a type of measurement that would place an approximate value on the potential services that could be provided from which an estimate could be made of the possiblity of achieving the established cost goals and thereby determine which features of a system should receive continued support. Inasmuch as it is not possible to place a value on human life or on personal injuries it may therefore, be necessary to consider the results in safety as a "plus" to the true economic evaluations that can be made.

With a highway toll of approximately 40,000 deaths per year and personal injuries far in excess of that number, there appears to be much less concern on the part of the public than there is for airplane accidents which total in deaths but a small number compared to the highway deaths. This limited concern may be due to the relatively small number of injuries per accident or the belief that nothing can be done about it. However, through the use of advanced electronic techniques, something can be done about it.

RCA has recently submitted a preliminary proposal to the Department of Commerce that a test roadway similar to that described, be built and a "systems study contract" be provided to a single organization to manage the project which would then include not only that prime contractor's interests but also those of other individual organizations and universities and highway workers generally. Such an approach will avoid wasted effort that is likely to result from a hit-or-miss approach involving individual devices and techniques. With some possible exceptions, elements of immediate highway vehicle automation should be compatible with the long range goals and devices adopted for immediate use should be modified, if necessary, to avoid getting into what could be an untenable position that would never permit consolidation into a system providing maximum advantage.

In conclusion, it is requested that key workers in the highway field take into committee for consideration the problem of how to establish a cooperative program at the earliest possible date. There may be disagreement on precisely what should be done but that should not deter from establishing a small group of knowledgeable individuals who would be able to outline quickly a program acceptable to all interested agencies. There is a great similarity between this situation and that in television about 20 years ago when cooperative projects involved technical development, legislation, program service, equipment service, manufacturing, and financing.

A few months ago, a special committee reported to President Kennedy and Secretary of Commerce Hodges that techniques had been developed for electronic control of highway vehicles and that further development and application to actual roadways should be expedited to hasten the benefits. Experience with large and complex systems has led RCA to the conclusion that implementation of 5 or 10 mi of automated highway, together with devices for installation on ordinary roads, would provide the most realistic next step.

It is of primary importance in establishing a test program that major and equal consideration be given to the objectives and the possibilty of practical use of these devices, rather than merely to prove that a technique can be successful in providing control but at a cost that would be unrealistic.

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

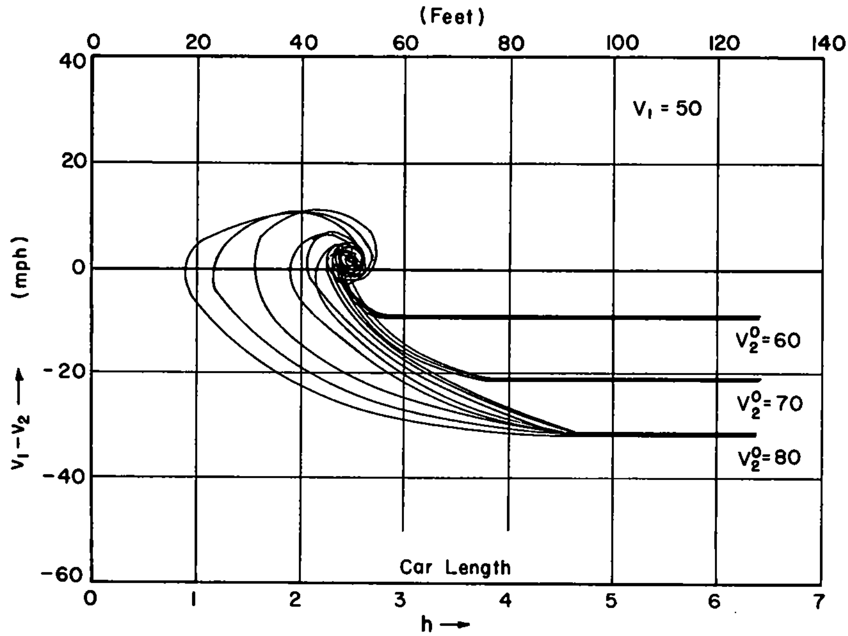

Figure 1. Phase trajectories of human driver overtaking lead car in automobile simulator.

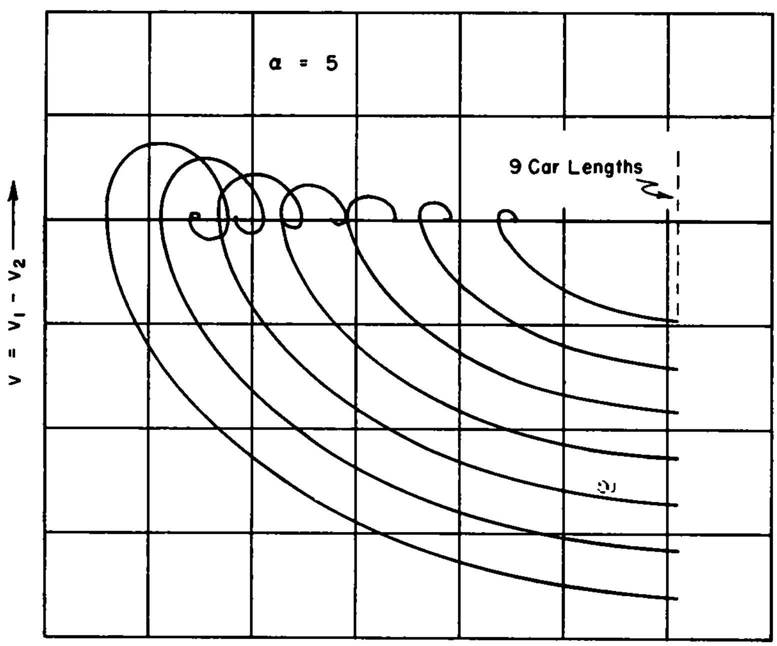

Figure 2. Analog computer solution of $a_{a_T} = \alpha \frac{v}{h}$.

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	$\lim a_2 = \infty \ h \to \infty$ 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	$\lim a_2 = K \ h \to \infty$ 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

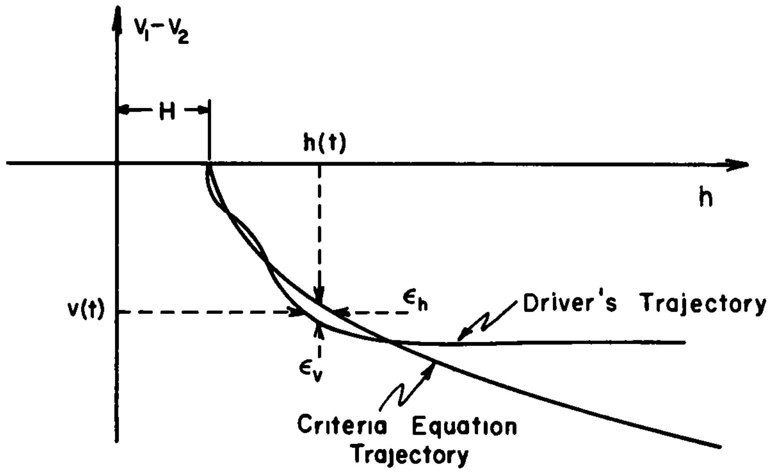

Figure 3. Comparison of driver's response with criteria.

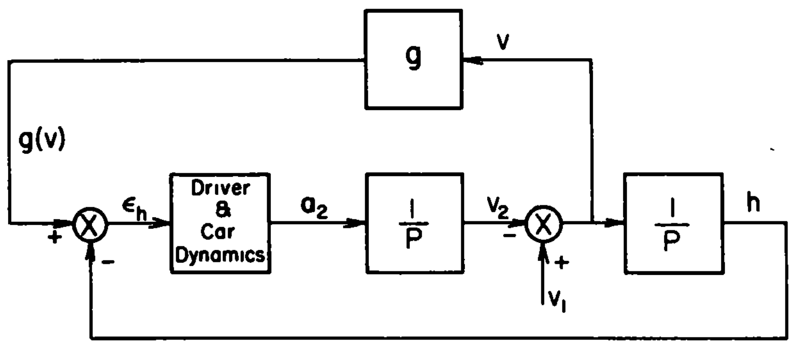

Figure 4. Continuous system with driver correcting headway error.

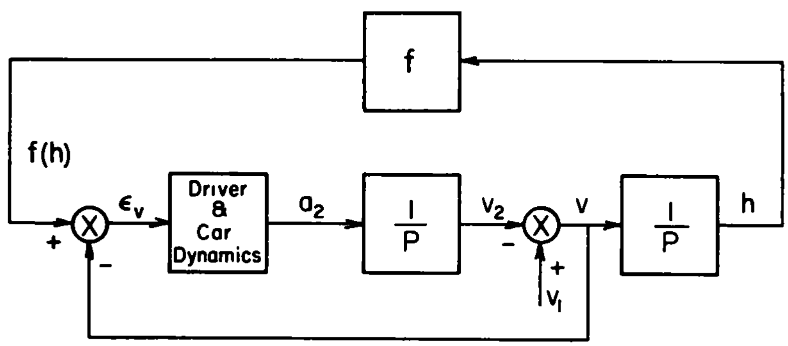

Figure 5. Continuous system with driver correcting velocity error.

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,

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

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

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

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

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

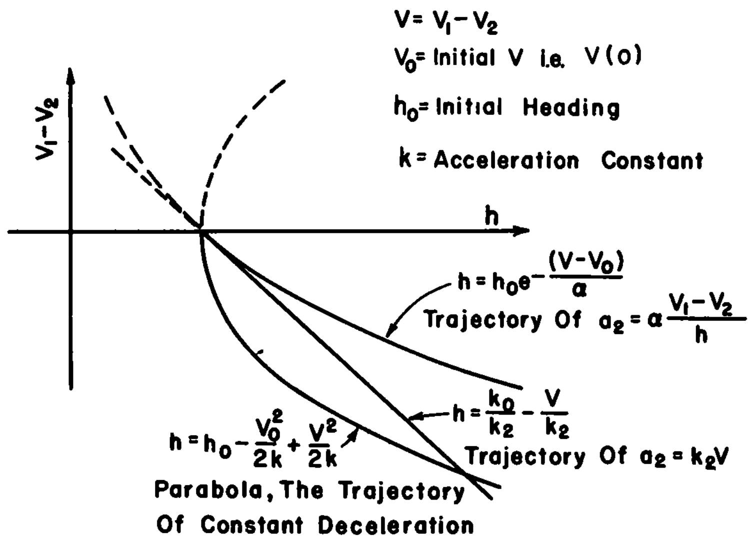

Figure 6. Possible g(h) functions.

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

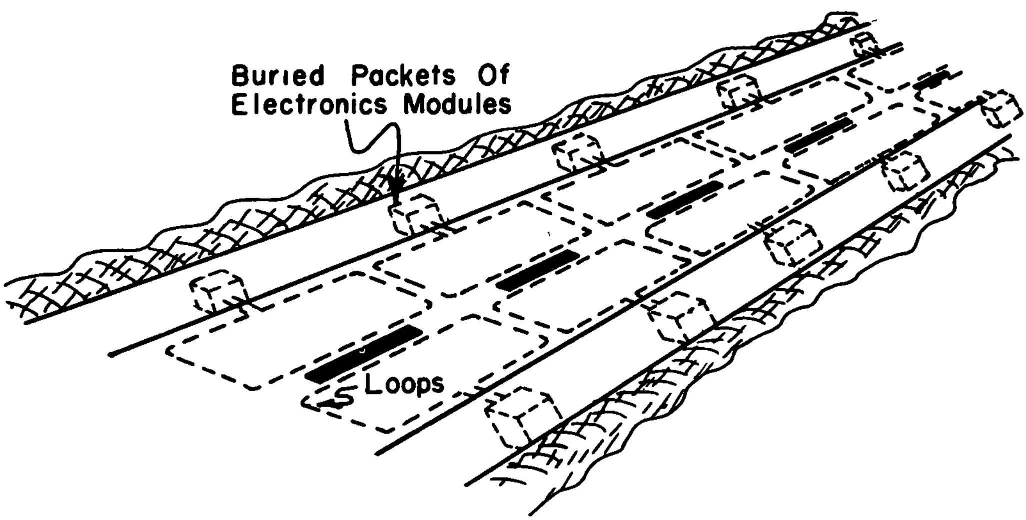

Figure 7. Physical highway layout.

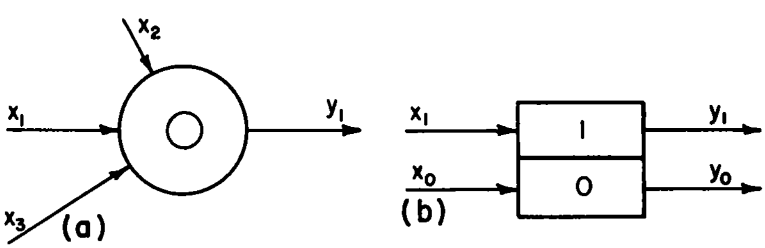

Figure 8. (a) "OR" circuit; (b) "Flip-flop" circuit.

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

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

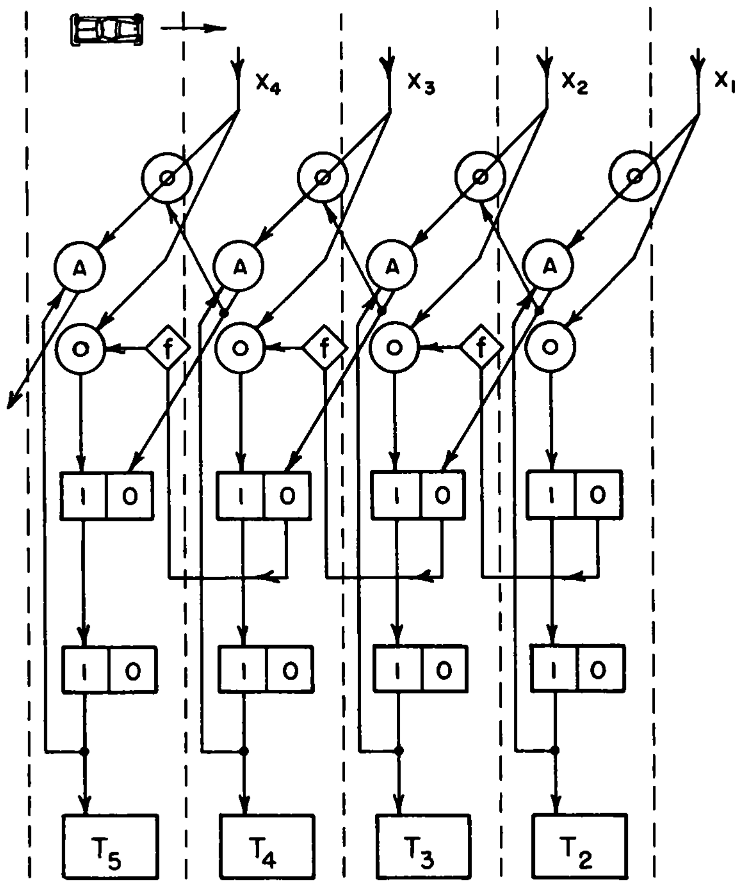

Figure 9. Highway logic circuitry.

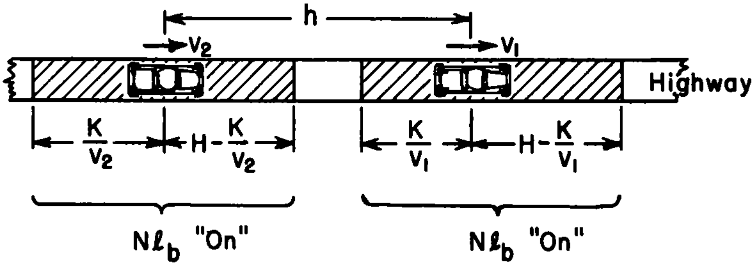

Figure 10. Zones of two cars.

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

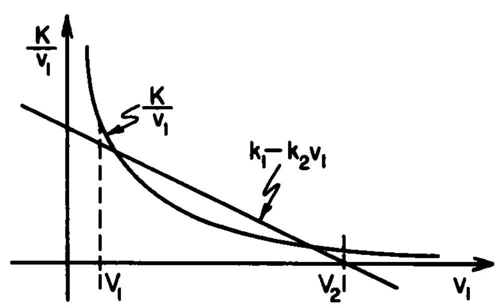

Figure 11. Approximation of $k_1 - k_2 v_1$ with $\frac{k}{v_1}$.

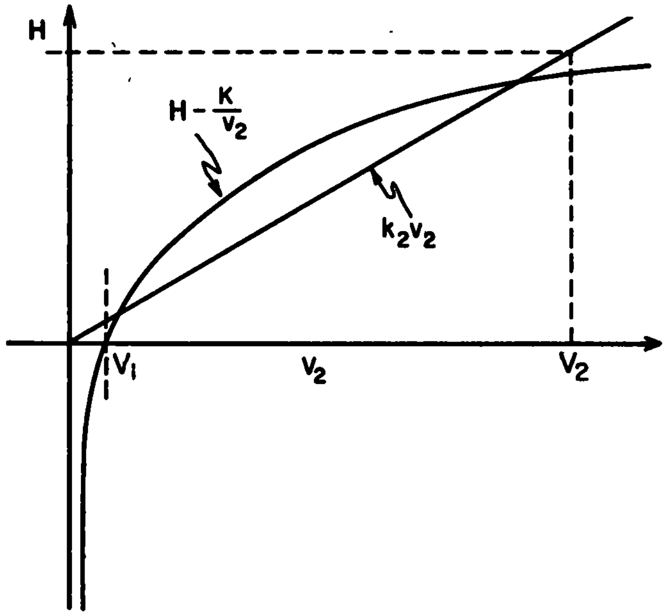

Figure 12 Approximation of k_2 v_2 by $H - \frac{k}{v_1}$.

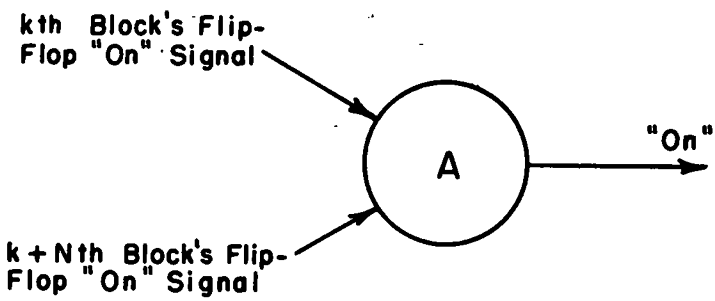

Figure 13. k^{th} block's "and" warning circuit.

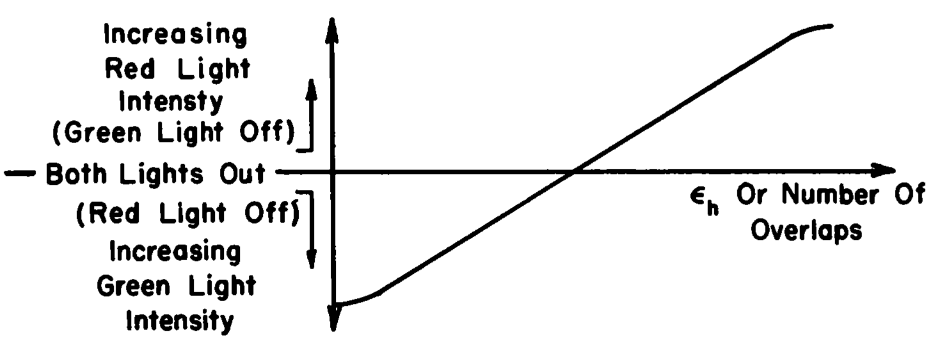

Figure 14. Warning vs overlap.

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.

REFERENCES

1. Barrick, D.E., "Automatic Steering Techniques." Antenna Laboratory Report 202A-2 (Dec. 1961).
2. Barbosa, L., "Studies on Traffic Flow Models." Antenna Laboratory Report 202A-1 (Dec. 1961).
3. Herman, R. (Ed.), "Theory of Traffic Flow." Van Nostrand (1961).
4. Greenberg, H., "An Analysis of Traffic Flow." Operations Res., 7: 79-88 (1959).
5. Pipes, L.A., "An Operational Analysis of Traffic Dynamics." Jour. Appl. Physics, 24:274-281 (1953).

A New Vehicle Guidance and Speed Control System

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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

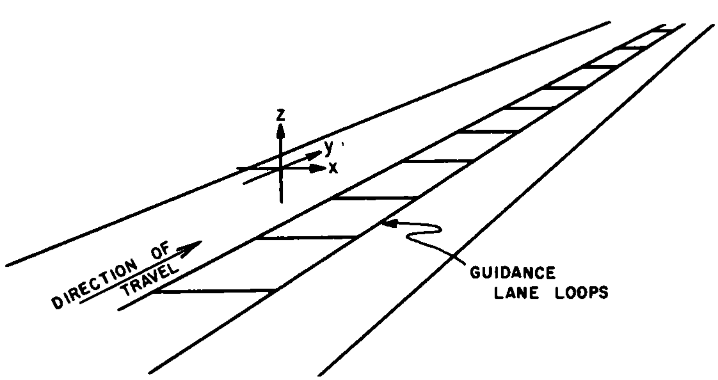

Figure 1. Three mutually perpendicular axes of excitor coil (z), guidance control detector (x), and speed control detector (y) in relation to guidance lane loops in or on highway bed.

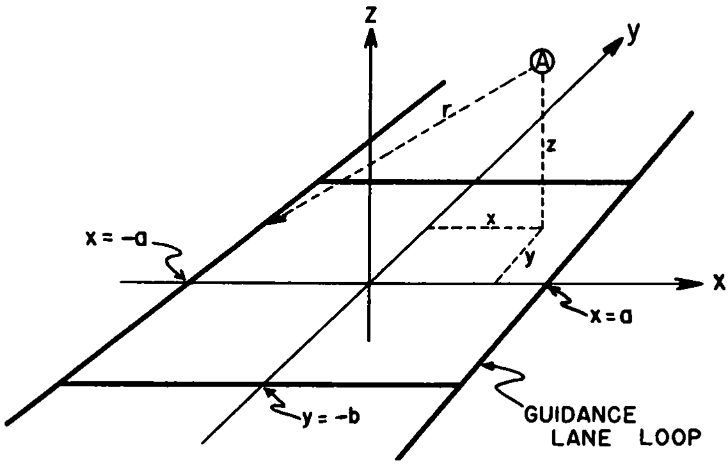

Figure 2. Coordinate system used to describe position of excitor coil and detector assembly (A) in reference to guidance lane loop.

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

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

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

and

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

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;

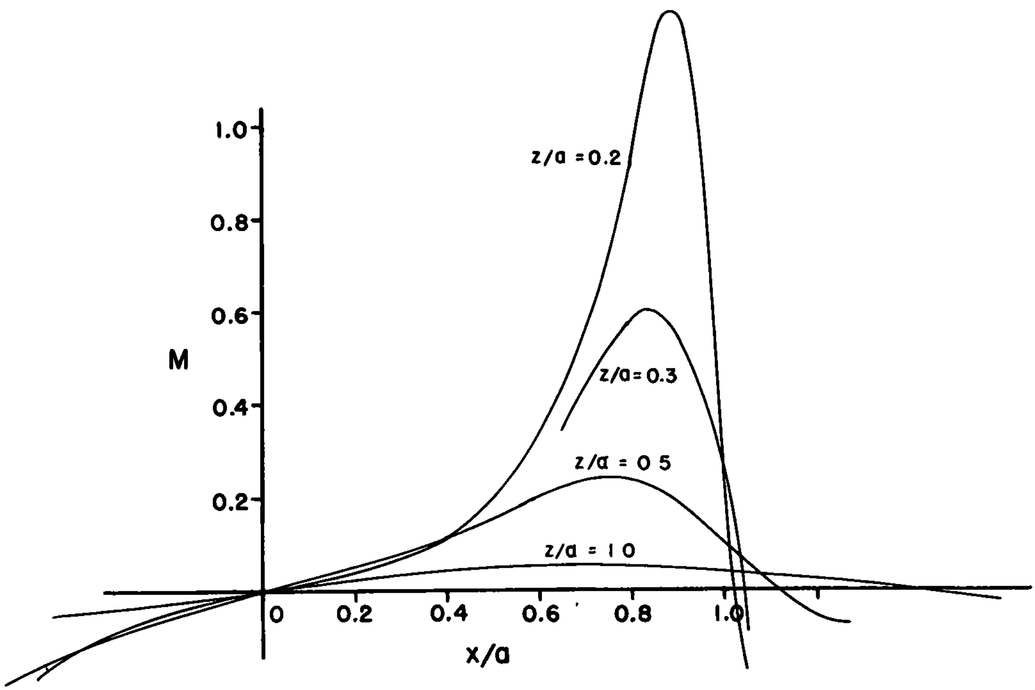

Figure 3. Plot of relative signal amplitude, M, as function of x/a at several values of z/a.

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:

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

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

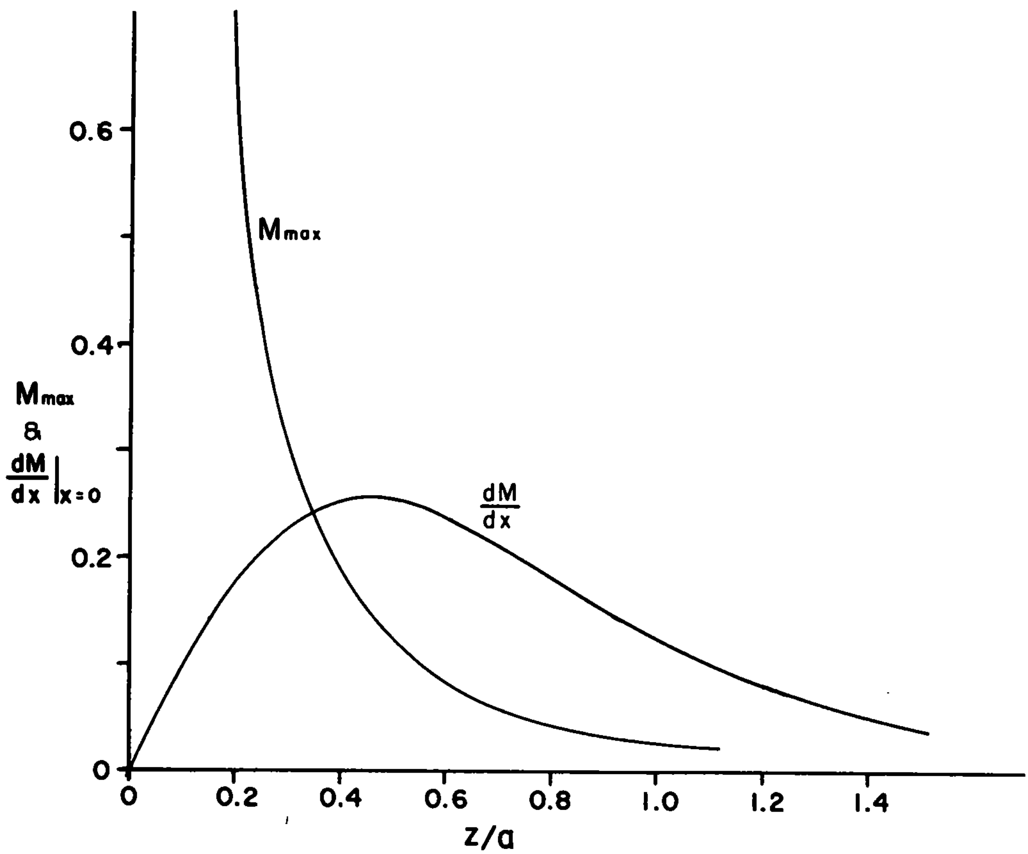

Figure 4. Plot of relative maximum signal amplitude, M_{max}, and $\left.\frac{dM}{dx}\right|_{x=0}$ as a function of z/a.

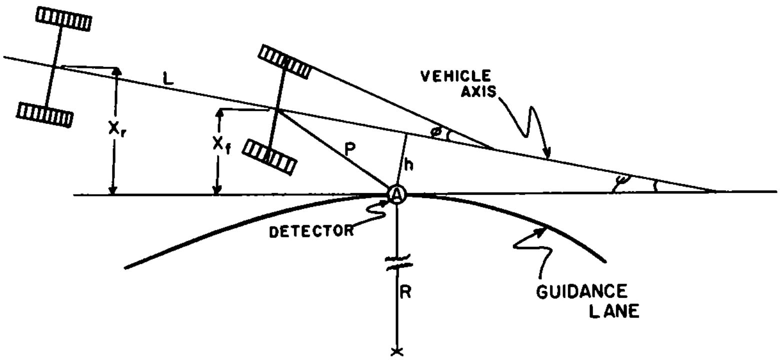

Figure 5. Drawing defining variables and system parameters used in text.

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

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.

REFERENCES

1. Ballerait, M.E., US Patent 2,803,743 (1957).
2. Hanysz, E.A., US Patent 2,965,188 (1960).
3. Paulus, C.L., et al., US Patent 2,317,400 (1943).
4. Zworykin, V.K., et al., US Patent 2,847,080 (1958).

Pilot Study of the Automatic Control of Traffic Signals by a General Purpose Electronic Computer

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• FROM THE BEGINNING of 1960 until the Spring of 1961 a network of traffic signals in a test area of Metropolitan Toronto were remotely operated by a general purpose electronic computer in a completely automatic, traffic responsive manner. The objectives of this experimental project were as follows:

1. To demostrate that an electronic computer could be connected into an existing traffic signal network to provide a very flexible, reliable, and very powerful coordinated signal system free of most of the limitations of existing traffic signal control equipment.
2. To obtain at least a first impression of how this powerful traffic control system could be used for improving traffic flow; for measuring the improvement; and for providing data on traffic to enable further improvement to be made.

The study was both a technical and an operational success and achieved both objectives. This paper summarizes the major aspects of the study.

ORIGIN OF THE SYSTEM

The impetus to develop and test such an unusual traffic signal system arose from a problem that is quite familiar to many traffic engineers. Present-day urban traffic is crowding existing streets to the limit and the traffic engineer must make the best use of every device at his command to prevent widespread traffic congestion. Frequently traffic problems are such that the only answer is to widen streets and build new overpasses and expressways, but the very high cost of providing new thoroughfares makes it imperative to use existing streets to their best advantage. By improving the efficiency of traffic flow by even a few percent in an urban area such as Metropolitan Toronto, the traffic engineer can save both the motoring public and the municipality many millions of dollars annually.

Effective control of traffic signals can play an extremely important part in keeping urban traffic moving freely. In rush hours especially, a signal system that can respond quickly to variations in traffic flow can do a great deal to reduce congestion and decrease delay.

From time to time, specialized forms of traffic signal equipment that respond in one way or another to traffic movements have appeared on the market, and the growing tendency in many American cities has been towards fairly heavy investments in this form of traffic signal modernization. However, though this equipment has aided somewhat in the improvement of traffic flow, its value in many traffic situations is rather limited. For example, none of this equipment can detect traffic congestion, and often will systematically aggravate rather than improve critical traffic conditions. In Metropolitan Toronto the best of such equipment would not significantly improve existing traffic situations, let alone those that may arise in the future. Available equipment, in spite of its advanced design, is simply not sufficiently flexible.

To deal with this dilemma a radically new signal control system was proposed that would have virtually unlimited flexibility in the manner in which traffic signals could adjust to traffic requirements. This proposed system would use a modern electronic computer to provide centralized coordinated control of the entire system of traffic signals. A network of traffic detectors would provide the computer with a continuous supply of information on traffic movements to enable the computer to calculate the best sequence of signal changes throughout the network. The computer would have direct and complete control of each signal and would continually readjust the signals to serve best the immediate traffic picture.

The system offered, in addition, a built-in facility for studying and improving the method of control, and for making long-range traffic plans. It would be flexible enough not only to adapt to future changes in traffic patterns but also to take advantage of future improvements in traffic control techniques and devices. The incorporation of computer control into the existing signal system could be carried out very smoothly, and because the bulk of the complex equipment would be located in the central control area, maintenance problems would be minimized. Full use would be made of existing equipment which would serve as a standby system in case of accidental loss of automatic control.

A system as comprehensive as this promised the traffic engineers and the roads and traffic committees a solution to many of their problems. Local interest was sufficiently great that a pilot study was commissioned to test this new traffic control system under actual traffic conditions. The computer-controlled signal system was put into operation, for the first time anywhere, in a test area in Toronto and has controlled traffic through a group of busy intersections for over a year.

PHYSICAL SYSTEM

The various components of the computer-controlled traffic signal system are shown in Figure 1.

Existing traffic signal controllers are equipped with a small modification unit connected by telephone lines to the remote central control area. When energized by a pulse from central control, the modification unit stops the internal timing mechanism of the local intersection controller and transfers control of the signal switch to the central control area.

Spare contacts on the signal switch (drum) are suitably connected to telephone cables to permit the signals showing at the intersection to be monitored at the central control area.

Traffic detectors located throughout the controlled area are connected to central control by a third set of telephone cables.

The central control equipment consists primarily of a general purpose digital electronic computer. A special input-output buffer connects the computer to the telephone circuits which terminate in the central control area. The function of the buffer is to convert the pulses coming from the traffic detectors and the signal monitors into a form suitable for input to the computer. Similarly, computed numbers transmitted from the computer are converted into pulses that produce remote operation of the signals. The input-output buffer also provides a visual presentation of vehicle counts and signal displays. A special digital clock provides the exact time in 1-sec intervals, enabling the computer to perform computations based on real time. The actual appearance of the central control equipment can be seen in Figures 2 and 3.

Figure 4 shows a map of the test area used in the pilot study. It is roughly 1.7 mi long and ½ mi wide. The initial test area consisted of nine traffic signals located on a busy east-west segment of Eglinton Avenue. Traffic detectors were located on almost all approaches at distances ranging from 200 to 600 ft back from the crosswalks. The final test area used in the last stages of the study consisted of sixteen signalized intersections.

During the course of the pilot study, the general character of the traffic signal system remained unaltered throughout the test area. The signal phases prevailing at a particular intersection before the study were retained. Restrictions on parking along the approaches and limitations to turning movements at the intersections were not changed. The only influences brought to bear on traffic movements as a result of the study were those produced by the automatic operation of the traffic signals alone. In the test area there was ample variety of traffic situations available for study. Traffic

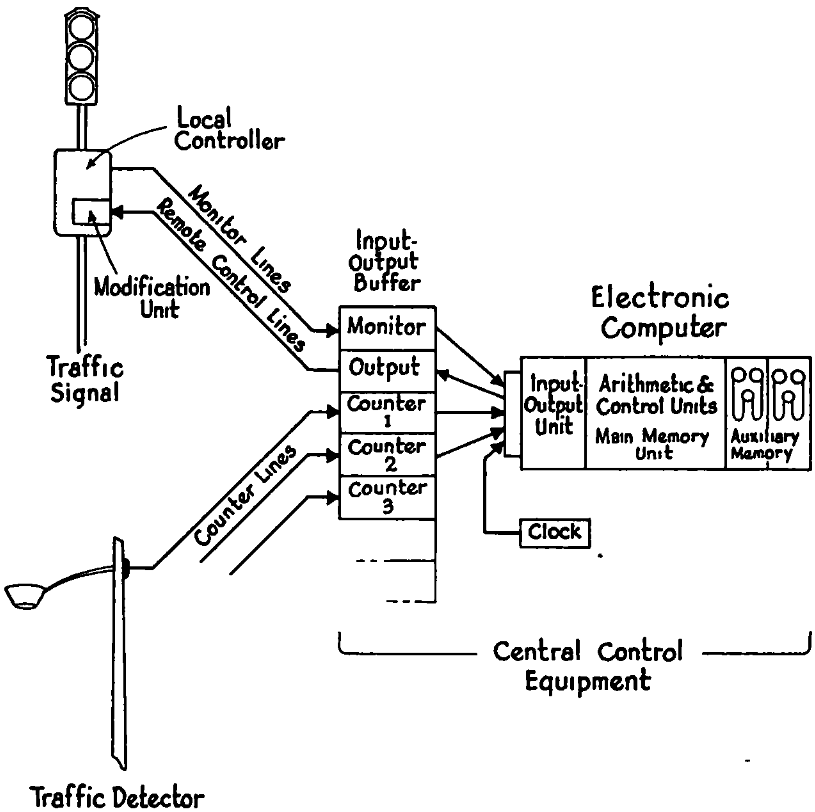


Figure 1. Components of automatic signal system.

movements varied over wide limits not only throughout the day as a whole but also within rush hour periods themselves.

SYSTEM OPERATION

The computer controls traffic signals by means of a master control program consisting of a large number of electronically stored instructions. These instructions, divided into groups of subprograms or subroutines, enable the computer to carry out a wide range of logical and mathematical operations relating to traffic movements and to the timing of traffic signals. For example, one of the subroutines instructs the computer how to initiate automatic control of the signals. Following a manual "start" order set up at the computer console, the computer begins reading in traffic data. As the computer observes each signal in turn advancing to a predetermined state (beginning of "main street" green), it energizes the modification units of the corresponding controllers and acquires direct remote control. The local timing dial is stopped in the dial-transfer position at the beginning of main street green and remains inoperative until released by the computer. From this point on, the signals can be changed only by the computer.

After automatic control has begun, further subroutines of the master control program enable the computer to analyze traffic data in order to operate the signals to best suit the measured traffic flow. Because of the large capacity of the magnetic tape units of the computer, a large number of control subroutines can be incorporated into the master control program.

Among these control subroutines are those enabling the computer to operate any signal according to any of the standard techniques. For example, one subroutine simulates the familiar volume-density control. When the computer follows this subroutine in controlling a signal, the effect at the intersection is identical to that obtained by having an actual volume-density controller installed at the intersection. Similarly, interconnected systems such as the P.R. system used in Baltimore and Philadelphia can be simulated by the P.R. control subroutine.

Even if the computer did no more than to emulate standard control techniques it would already have a flexibility far beyond that obtainable with fixed-purpose hardware. All of the adjustments that must be made locally at the Volume Density Controller or at a P.R. controller are made centrally within the computer. To change intersection control from P.R. to volume density would normally involve reinstallation and rewiring of equipment at the intersection. With computer control it involves merely a manual change of a switch or an internal change automatically generated by the computer itself. A network of traffic signals can be functionally regrouped as often as desired according to whatever scheme is desired without any rewiring or readjustment of equipment.

Figure 5 shows such a network of traffic signals under the control of the computer. Because of the way the master control program is designed, the signals can be combined into any prearranged grouping and each group operated according to a different set of criteria if so desired.

The computer, however, can go far beyond merely simulating existing automatic signal systems. New concepts of traffic control can be developed and introduced. Because the computer system is not functionally limited by fixed purpose wiring and equipment, it does not become obsolete. The complexity of control is limited only by

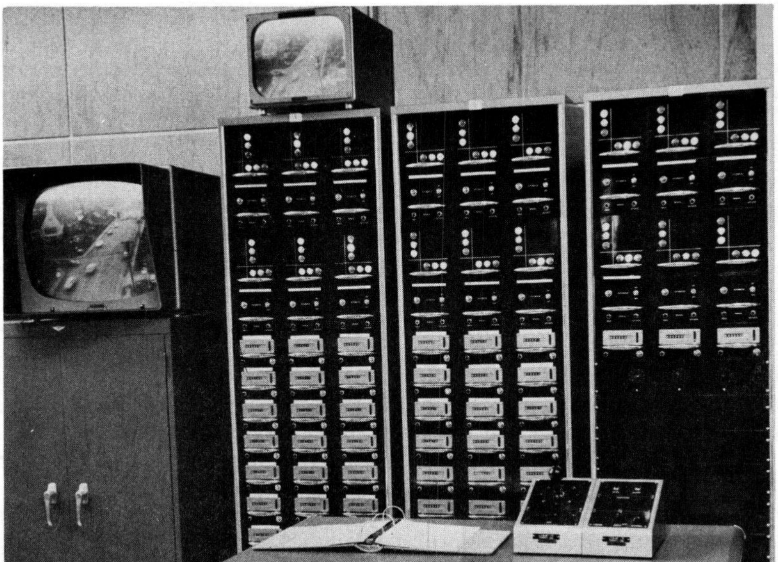


Figure 2. At remote control center located over 2 1/2 mi from test area, a special display unit indicates the signals showing at each intersection and records passage of vehicles past various detectors. This information is transmitted in coded form to electronic computer located in adjoining room.

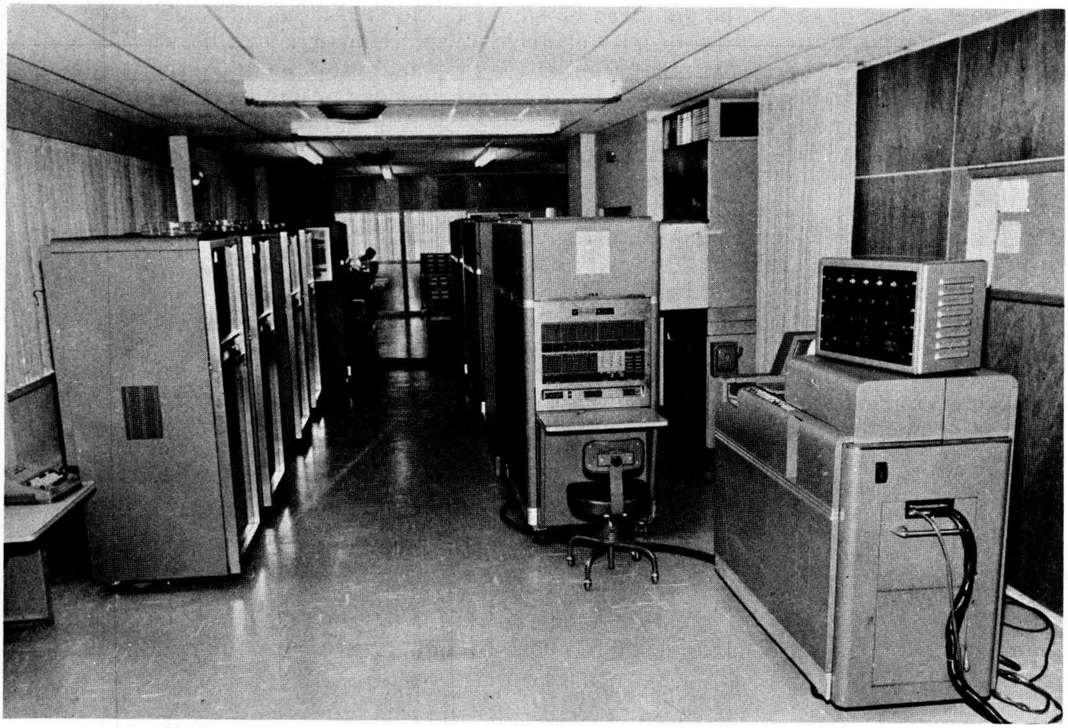


Figure 3. Electronic computer used to control traffic signals in test area examines traffic movements, computes coordinated timing schedules, and puts them into effect. During period of automatic control, computer has direct and exclusive control of each traffic signal.

the ingenuity of those designing and producing the control programs and by the ultimate speed and capacity of the machine.

During automatic control, the computer follows a control plan that is to be put into effect. As shown in Figure 5, several different control modes may be involved in a single control plan. The change from one control plan to another may be brought about manually at the computer console or may be made to depend on computed index described prevailing traffic flow.

In addition, the computer has tables of data that describe the physical characteristics of each intersection, such as the number of lanes on each approach and the distance of the detectors from the crosswalk. Thus, whichever general principles of control are being applied, they are specialized to suit each individual location. Figure 6 shows some of the logical functions of the master control program used in the pilot study.

During automatic control the computer continuously repeats the following sequence of actions: it reads in all current traffic data, the detectors, monitors, and clock. Computations are carried out for each intersection in turn to determine which signals if any should be switched. An output pulse is transmitted to carry out any necessary actuations and the monitors are immediately rechecked to see that the actuations (if any) were carried out correctly. This computational sequence is completely repeated every 2 sec. Any malfunction of the equipment will cause the computer to release control to the local intersection or intersections, depending on the extent of the malfunction. While control proceeds, a complete record of traffic and control data is stored on magnetic tape for later analysis.

The end of a period of computer control may be determined by a preset time the clock eventually reaches, or by a manual change of a switch at the console. When the computer receives the "terminate" instruction, it continues controlling the signals until it has advanced each signal through the completion of a normal cycle into the beginning of "main street" green phase. Control is then released back to the local signal controller which picks up where it left off in a completely smooth manner.

After a period of automatic control, the same computer that operated the signals is now able, by means of special data reduction programs, to analyze the traffic records stored on magnetic tape. Thus, the influence of various control schemes on traffic can be studied and new control methods can be planned.

METHOD OF CONDUCTING TESTS

To take full advantage of the flexibility of the computer it was necessary to develop new methods of controlling traffic. In addition it was necessary to evolve methods of dealing with the large amounts of centrally recorded traffic data for the purpose of evaluating different methods of control.

As a starting point, attention was focused on the capabilities of existing traffic control systems. During the summer of 1960 considerable work was done on the qualitative testing of the best of currently developed traffic control systems including the familiar volume density and P. R. systems. The benefits and shortcomings of these control methods were clearly exhibited. Meanwhile, the control programs were further developed to introduce concepts of traffic signal control that had not been used anywhere before. For example, there was incorporated into the control programs a computational method by which the computer could detect the presence of congestion and take corrective action to help clear it up. At the same time analytical techniques were evolved for objectively studying traffic movements.

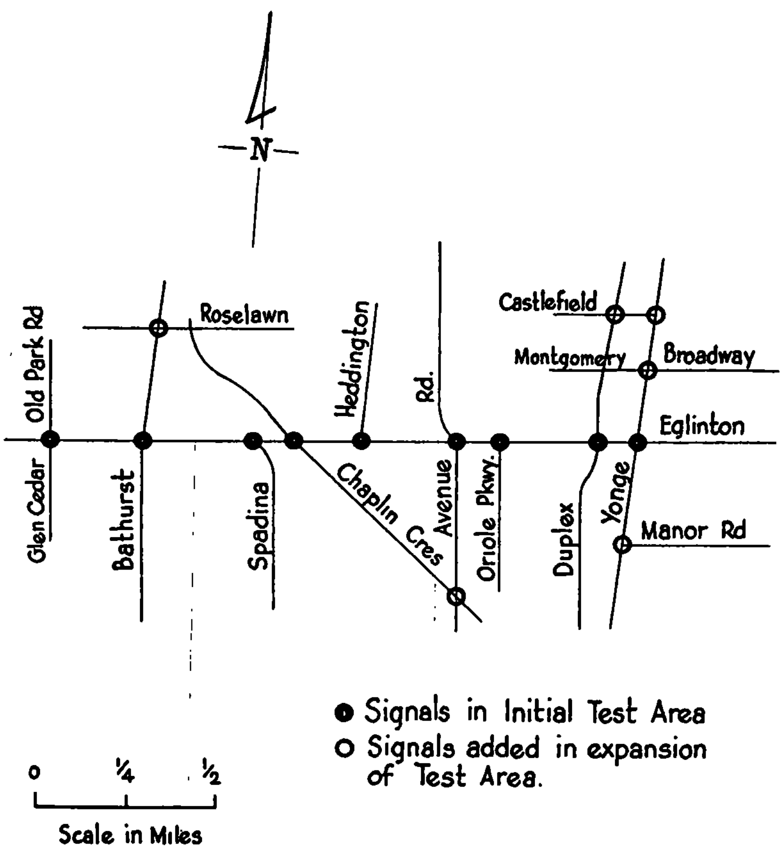
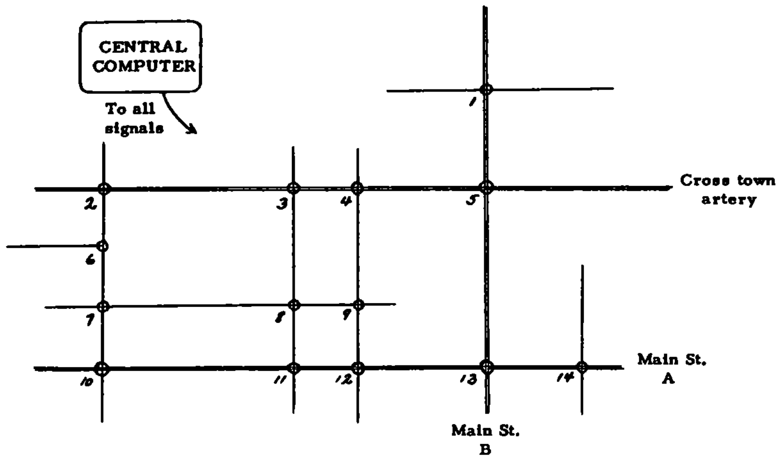


Figure 4. Expanded test area.



Plan I Midday Normal Traffic

#1, 7, 8, 9, 10, 11, 12, 13, 14 ------ Mode 1 Control (Density)
#2, 3, 4, 5 --------- Mode 2 Control (Progressive)
#6 --------------- Mode 3 Control (Semi-Actuated)

Plan II Rush Hour Heavy Traffic

#1, 5 ------------- Mode 1 Control (Density)
#2, 3, 4, 7, 8, 9, 10, 11, 12, 13, 14 --- Mode 2 Control (Progressive)
#6 ------------- Mode 4 Control (Semi-Actuated Progressive)

Plan III Evening Traffic

#6 Semi-Actuated Progressive
All others Progressive

Plan IV etc.

Figure 5. Example of control of traffic signals according to different grouping plans.

The pilot study has shown that the recorded data is sufficient to produce close estimates of travel time, delays, and congestion without the necessity of field observations (except for corroborative proof). Information such as average volumes and space-time charts are readily produced. The arithmetic necessary to derive these figures can be performed by the computer very easily because the raw data is recorded in a form compatible with computer input.

A detailed account of the many ways the recorded data were used for evaluating traffic movements is beyond the scope of this paper. The following discussion, however, illustrates some of the uses to which these data were put.

Platoon Structure and Travel Time

Some of the most interesting results are obtained by examining the counter information in conjunction with the monitors. One of these is the study of platoon structure.

A question fundamental to deciding on the best offsets between signals in a progressive system is a knowledge of how long it takes drivers to go from one intersection to another under varying conditions, and also how platoons spread out between intersections.

This can be derived from the recorded data by considering the cars arriving at a given counter relative to the time the previous signal became green for this direction, as shown by the appropriate monitor. Figure 7 shows an example of platooned structure for southbound vehicles arriving at Bathurst-Eglinton in each 5-sec interval after the signal at Roselawn changes to southbound green.

When both the size and shape of the usual platoon and also its timing relative to the preceding signal is known, it is possible to set the average offset of the following signal in a manner often superior to the usual method of allowing a first vehicle in a platoon to proceed unhindered at an assumed speed.

Delays

To measure delays to vehicles on an approach to an intersection it is necessary to keep track of each vehicle from the time it reaches a certain point on the approach until it enters or clears the intersection. The time required to do this is the actual travel time. By subtracting the time required for an unobstructed car to travel the same distance, an estimate of the delay caused by the signal and by other vehicles is obtained.

To do this in practice is difficult because the information received and recorded by the computer includes the time of passage of every vehicle at the detector, but does not include the time of release or clearance through the intersection. It is therefore, necessary to make some assumptions (based on actual observations) about the normal travel time from detector to crosswalk, the period and rate of release, the probability of a car entering one or other of a multilane queue depending on the length of the queue.

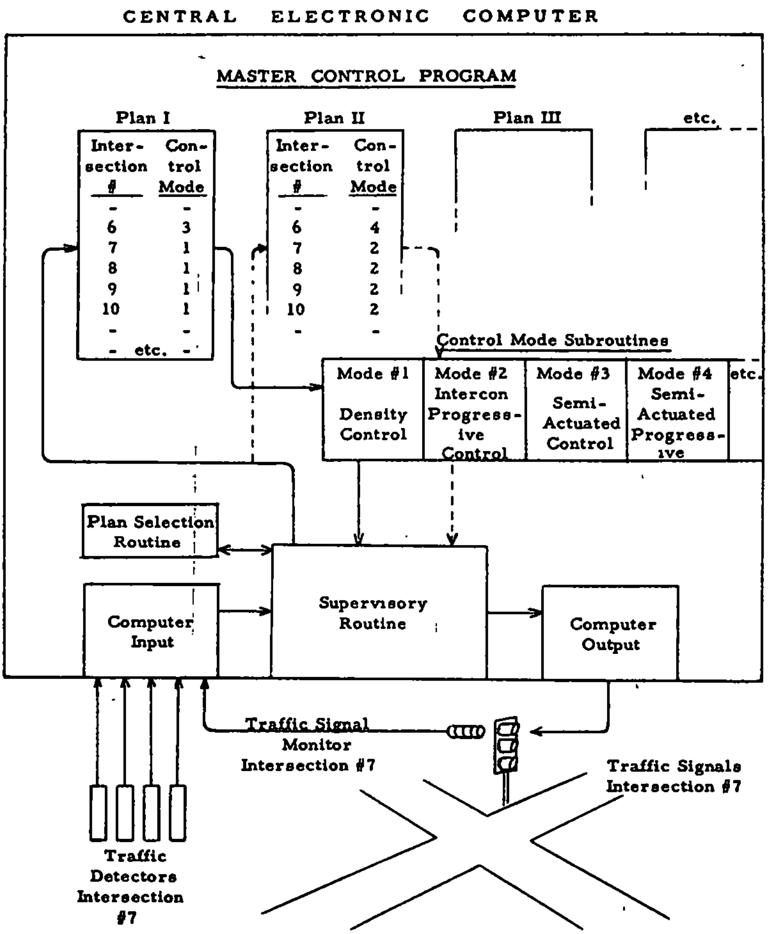


Figure 6. Computer consults control plan to determine mode of actuation to be given to a particular intersection.

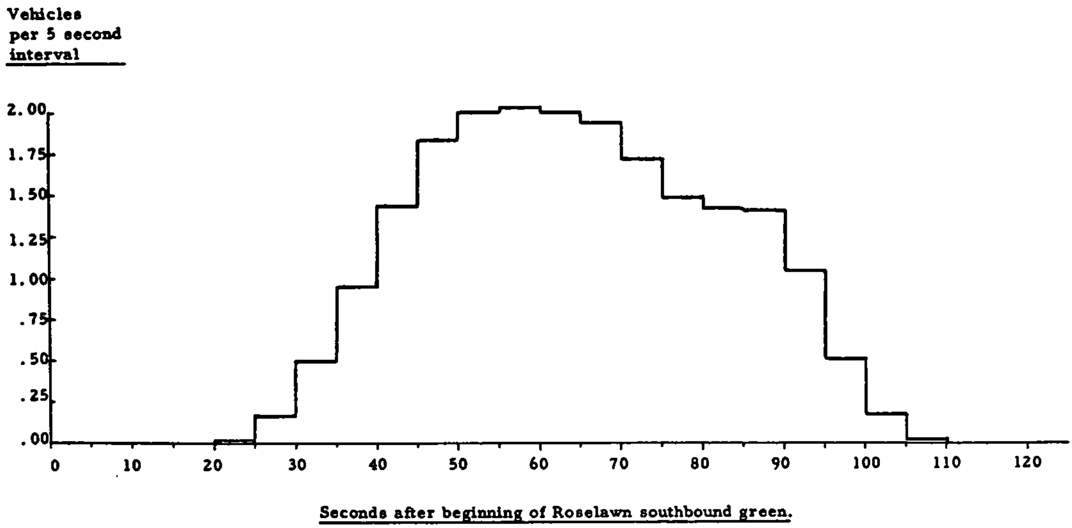


Figure 7. Histogram showing number of southbound vehicles arriving at Bathurst - Eglinton in each 5-sec interval after light at Roselawn turns green for southbound traffic. It indicates, for example, that from 50 to 70 sec the arrival rate is about two cars in each 5 sec or 0.2 cars per sec per lane (there are two lanes). Also about 3 percent of platoon arrives in less than 35 sec, better than a 30-mph average.

To check the accuracy of the calculated delays, speed and delay runs were carried out in the test area. Table 1 compares the average delays as determined by the computer with the actual delays noted in the field tests. As the table shows, the agreement was excellent.

TABLE 1

OBSERVED VS CALCULATED DELAYS

Street	Traffic Direction	Delay (sec)		No. of Observations
		Observed	Calculated	
Bathurst	Eastbound	29.8	30.3	100
	Westbound	43.4	44.8	84
Avenue Road	Eastbound	33.0	33.8	113
	Westbound	36.8	36.6	15

Congestion

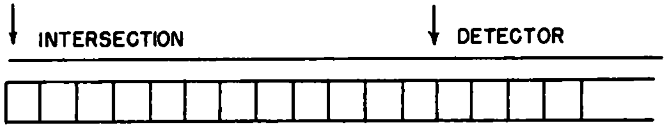
Traffic congestion is a rather subjective concept. For the purposes of the study an approach to an intersection was considered congested whenever the queue of waiting vehicles extended past the detector.

The reason for this definition is that in most locations the detectors were mounted approximately 300 ft back from the crosswalk. A green time of 30 sec can clear a 300-ft queue of about 12 or 13 vehicles per lane. Hence, in most cases a queue that extends beyond the detector position may not clear on a normal green period. If the queue extends past the detector throughout the entire cycle, it is definitely excessive and may in fact be interfering with movement at preceding intersections.

The measures developed for determining when excessive queuing is present were based on the pattern of movement past the detector relative to the timing of the traffic signal.

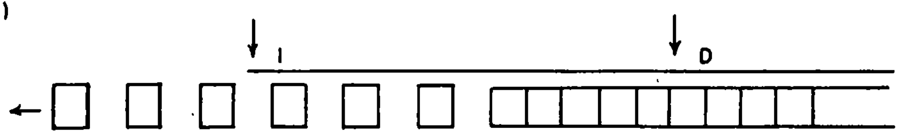
Case A. —The queue extends well past the detector

(i)



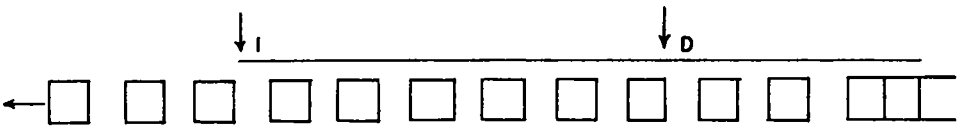
When the signal light turns green there is no movement under the detector. The vehicle at the head of the queue starts to move.

(ii)



A few seconds afterwards, there is still no movement under the detector, but the motion "wave" is approaching at the rate of 100 ft in 6 sec. (This is an experimental result.)

(iii)



After the motion wave reaches the detector, detections occur at the rate of one every 2 to $2\frac{1}{2}$ sec (on each lane), until either the end of the queue clears the detector or the movement is stopped again by a red light and the queue has closed up.

Case B. —The end of the queue does not reach the detector. The pattern of arrivals is determined by the preceding intersection and, except in the case of a progressive system, bears no relation to the observed intersection. In the case of a progression toward the intersection, the head of the arriving platoon should pass the detector just before the signal turns green, so that movement at the detector would occur at a different time relative to the signal than it would with a long queue.

Figure 8 shows how these results appear in the plots of recorded data.

By early Fall, the preliminary testing was completed and a carefully planned evaluation study conducted throughout the test area. Morning and evening rush hour periods were studied under various forms of automatic control and under the usual fixed-time control. To provide a thorough check on the computed traffic picture, field observers from the local traffic engineering staffs were stationed at all important intersections to record special details on traffic movements through all rush hour periods of the study. Test cars driving through the system at carefully recorded times provided actual experience of speed and delay. The results of this special test program, which extended over a month's time, formed the basis for judging the value, at this fairly early stage of development, of the computer-controlled traffic signal system.

While this special evaluation project was under way, the test area was expanded to its final form with all 16 traffic signals under automatic operation by late Fall 1960.

RESULTS OF PILOT STUDY

A comparison of the automatic system with the existing fixed-time system during the special evaluation tests produced the following results.

In the evening rush hours, the automatic system decreased the average delay per vehicle by some 11 percent. In the morning rush hours, the average delay per vehicle decreased by 25 percent, and congestion was reduced by 28 percent.

To the average driver, this means rush hour speeds that often average less than 12 or 13 mph can be increased to over 16 mph. To the traffic engineer it means that for a given delay, traffic volumes may be increased up to 20 percent.

These figures describe the performance of the automatic system developed only to an intermediate stage of efficiency. With further development of the control programs and with extended control of traffic on an area basis, greater benefits may be anticipated.

From the standpoint of reliability, the automatic traffic system performed extremely well. The most complex components, the central computer and associated equipment gave virtually no trouble at all. A single style of modification unit served to convert each of the signal controllers for automatic operation without compromising any of the normal fixed-time functions. The transitions from periods of fixed-time control to automatic control and back again was completely smooth. The only components that gave less than expected reliability were the traffic detectors. The type used during the study proved to have too short a service life to enable its consideration as an economical component of a final system.

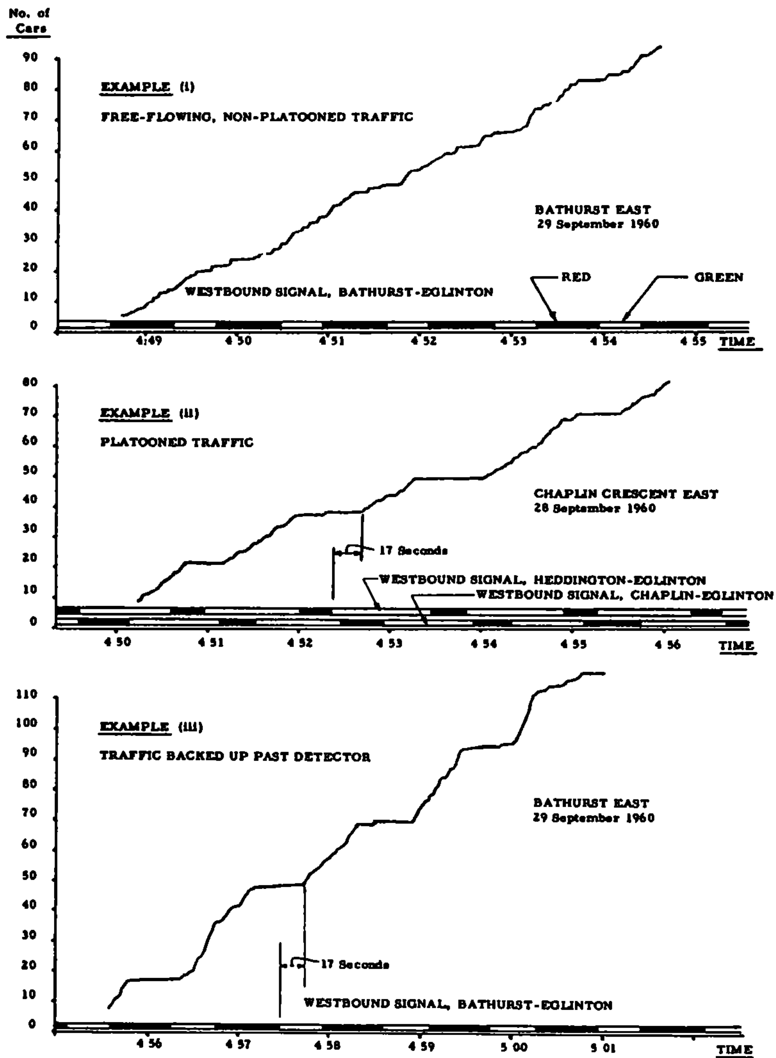


Figure 8. Congestion patterns.

In anticipation of this problem, a separate program of detector evaluation was undertaken during the pilot study to test various types of detectors and to experiment with new prototype units. Recent developments indicate that not only may the reliability problem be solved but the installed cost of the newer devices may be considerably less than those encountered in the pilot study.

A FULL-SCALE SYSTEM

The pilot study has demonstrated that with an electronic computer as the basis of control, a powerful traffic signal system can be realized that is practical for city-wide installation.

It is reasonable to assume that a full-scale system would provide benefits citywide which should be comparable to those achieved in the test area, for the following reasons:

1. A wide range of traffic situations were encountered in the test area, some of which are as difficult to control as any in Metropolitan Toronto.
2. The control programs used in the evaluation tests were developed only to a relatively early stage. With further development in the light of increased experience in traffic control, greater benefits should result.

The value of extending the benefits achieved in the pilot study throughout the entire Metropolitan Toronto area is outlined next.

It has been estimated that in the metropolitan area over 50,000 vehicle-hr of delay are caused by rush-hour traffic congestion every day. Conservative estimates place the costs of fuel and general wear and tear to vehicle in congested stop-start driving at about $0.90 per hr. This makes no allowance for the cost of personal time.

If the results of the pilot study were extended throughout the entire traffic area we could expect a reduction in total traffic delay exceeding 9,000 vehicle-hr daily. This would amount to a direct saving to the motoring public of over $2,000,000 per annum in vehicle operating expenses alone.

In addition, the effective increase of peak capacity of the road system would provide an immediate benefit that would otherwise require some $20,000,000 to $40,000,000 for widening existing street facilities or building new roads.

The major traffic area in Metropolitan Toronto is controlled by a network of some 500 traffic signals. To operate these signals with an automatic system that would provide a good compromise between performance and initial cost, yet could be expanded to whatever limit of future complexity it was economically feasible to go, would cost some $3,500,000 to install and about $200,000 per annum to operate.

The Municipality of Metropolitan Toronto is presently considering this course of action as a sound investment.

Traffic Pacer

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This paper deals with the design and evaluation of a traffic pacer system installed on a highway near the General Motors Technical Center. The traffic pacer causes changing speed signs and stop signs between intersections to group traffic so that it may pass through the intersection with a moving start. The control system is intended to increase intersection capacity and reduce delays and trip time.

• ON CONVENTIONAL urban and suburban street systems, the capacity is limited by the performance of the intersections. The traffic pacer is a traffic control system that uses accurate phasing of successive signals along with supplementary speed information for the driver to maximize intersection capacity and thus obtain greatest system capacity. In addition, by controlling their car speed in accordance with the sign information, drivers can avoid the necessity of intersection stops by arriving during the green phase. So that a meaningful evaluation of the traffic pacer system could be made, two systems now in use (a noninterconnected system and an interconnected system) were compared with this unique system for a period of 12 weeks.

The criteria used to compare the three systems were (a) average trip time, average number of stops, and average velocity for the 4-mi experimental testing area; (b) intersection capacity; (c) queue length; safety; (d) and public opinion. All system parameters were kept as constant as possible. A balanced experimental design was utilized to minimize any effect that changing environmental variables might produce.

HISTORY

In 1954, Wolfgang von Stein installed the first traffic funnel in Dusseldorf, Germany. Since then, the popularity of the speed signals and presignals that compose the German Traffic Funnel has grown so that today there are over 200 of these novel traffic control devices throughout Europe. In 1958, Arthur Underwood contacted von Stein, after having driven through the Dusseldorf Traffic Funnel while in Europe. In December 1959, von Stein gave a paper (1) at the Theory of Traffic Flow Symposium held at the General Motors Research Laboratories. Although the actual hardware used in the traffic pacer is different than that used in the German counterpart, the basic control philosophy is the same. So that the traffic control system has a more pleasing connotation to the driver, the name traffic funnel was changed to traffic pacer for the American version.

The German experience has demonstrated that there have been three main improvements attributable to the speed and presignals:

1. A two-car-per-lane-per-cycle theoretical increase in capacity.
2. An increase in safety.
3. A decrease in stops.

The first U.S. traffic pacer installation was placed in operation on Mound Road extending from 11 to 15 Mile Roads in Warren, Mich., on July 31, 1961, to test the pacer's merits. The Macomb County Road Commission owns and operates the pacer system, but the entire project cost and operating expense have been borne by General Motors.

OPERATION OF TRAFFIC PACER

The object of the traffic pacer is to form compact groups of moving vehicles, timed to arrive at the intersection at the onset of the green phase. As the last car of the artery group of vehicles passes, a time gap should be provided in artery flow. This gap should be large enough to allow the crosstraffic to pass. To accomplish these goals, the traffic pacer employs two extra control elements that are not used in the ordinary interconnected progressive traffic systems: speed signals and pre-intersection stop signals. The latter element shall be referred to as a presignal. These control elements are shown in Figure 1. The elements are from front to back, a speed signal, two presignals with a speed signal mounted in between them, and the normal intersection traffic signal. A telephoto lens has compressed the distance between the elements. The distance between the speed signal and the intersection traffic signal is approximately 1,500 ft. The indicated speed on the speed signal varies according to

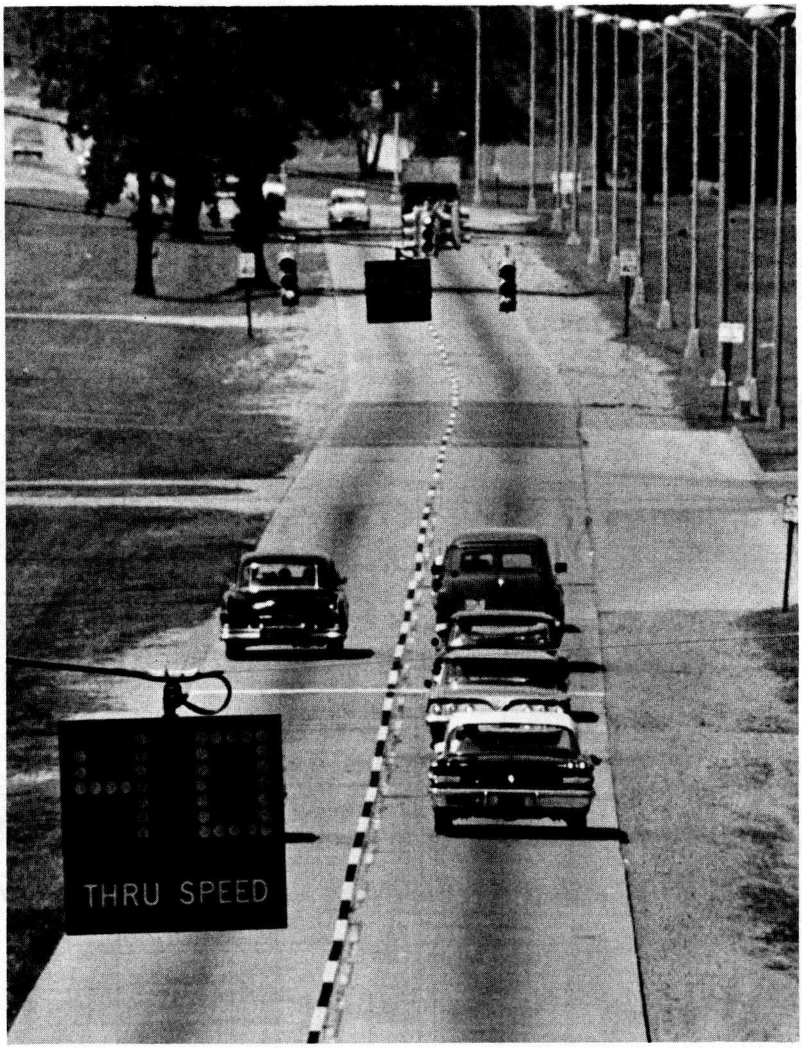


Figure 1. Traffic pacer control elements—speed signal in foreground, speed and presignal in near background, intersection signal in background. Legend changed beneath speed signal to read "Begin Thru Speed Here."

the vehicle's time of passing the signal. In other words, vehicles at the end of the group are told to travel faster than vehicles that have already passed the speed signal, thus concentrating the vehicles into a more compact group. In every instance, the maximum speed limit shown by the signals is the maximum speed limit of the highway. Figure 2 is a typical time-space diagram showing precisely how this is accomplished. The shaded areas between the two intersections indicate the segment of the time-speed plot that drivers should avoid if they want to arrive at the next intersection during the green light phase. The slope of the lines indicates speeds the drivers must maintain to keep within the lighter zone, thereby arriving at the next intersection during the green light phase. The first speed signal has a cycle that changes from 25 to 30 to 40 mph. The speed and presignal installation has a cycle that changes from amber to red, to 25 to 40 mph. The diagram shows, for example, that a driver leaving intersection 1 at the beginning of the red light interval A will reach intersection 2 at the beginning of its green light interval B by maintaining a 30-mph speed. Similarly, a driver leaving intersection 1 halfway through the light cycle at C will reach intersection 2 at the start of its green light interval at B by maintaining a speed of 40 mph. Finally, the last vehicle of the group, leaving intersection 1 on the amber signal at D, will reach intersection 2 on its amber signal at E by also maintaining a 40-mph speed.

The purpose of a presignal is to provide a moving start. Even rapidly accelerating vehicles, when starting from a standstill, lose from 3- to 6-sec headway compared with vehicles that have been paced for the intersection signal. By releasing the traffic behind the presignal early, these vehicles that have had to stop for the presignal will arrive at the intersection with a moving start just as the intersection light turns green. Figure 3 shows in a time-space diagram with a 20-sec intersection green how a presignal can increase the capacity of an intersection. In both diagrams, the intersection's traffic signal has a 50-sec cycle consisting of a 20-sec green, a 3-sec amber, and a 27-sec red light interval. In the pacer system, the presignal green is longer than that

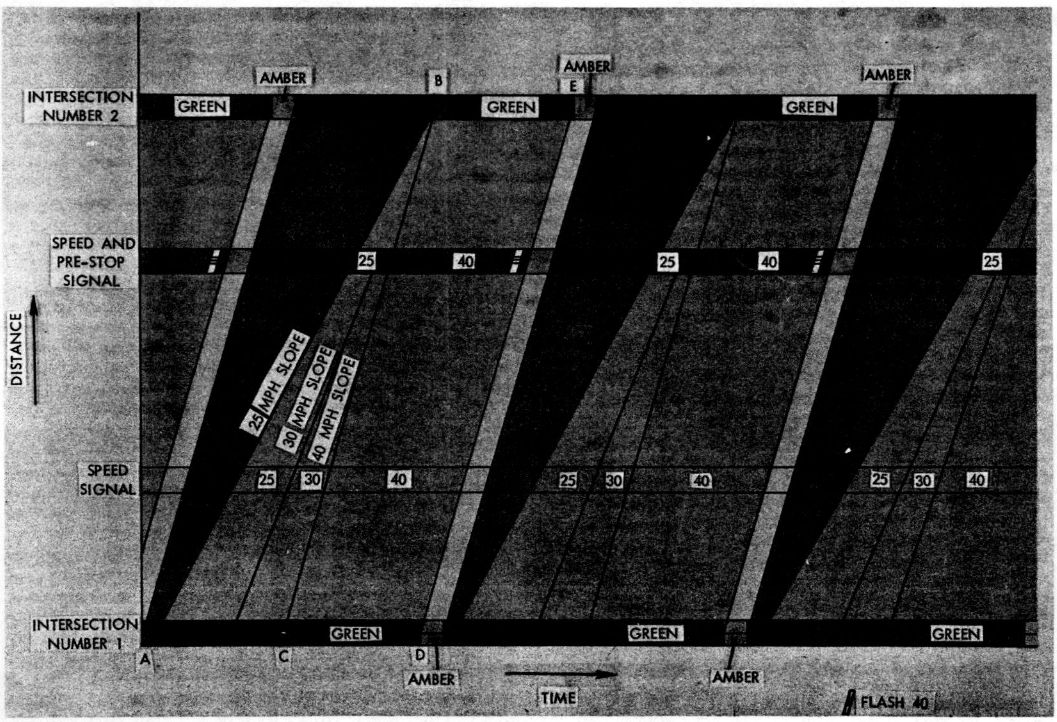
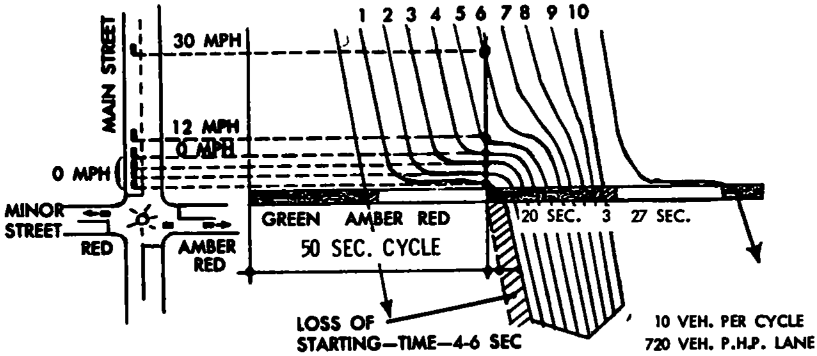


Figure 2. Simple time-space diagram.

TIME-SPACE DIAGRAM WITH NORMAL START



TIME-SPACE DIAGRAM WITH MOVING START

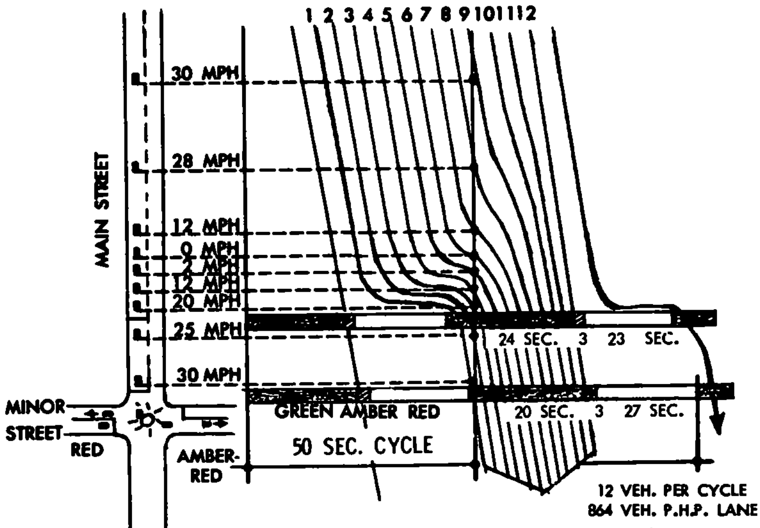


Figure 3. Time-space diagram demonstrating two-car per cycle gain for an intersection with a presignal.

at the intersection (in this example, 24 sec) to provide for acceleration time. In the normal crossing where vehicles stop immediately before the intersection (top), the first four or five vehicles in the group require from 4 to 6 sec to regain the 30-mph speed when accelerating from a standing start, forcing vehicles behind them to slow down as they approach the intersection. In this example, 10 vehicles per cycle are permitted to cross the intersection giving a 720-vehicle per hr per lane capacity. By installing a prestop signal (bottom), however, vehicles that arrive at the intersection during the red light interval are halted before the main intersection. When the prestop signal turns green, the first vehicles in the group can accelerate to the 30-mph maximum speed by the time they reach the intersection, thus eliminating the starting time loss incurred in the normal crossing system. This prestop signal permits 12 vehicles per cycle to cross the intersection, thus increasing the highway's capacity to 865 vehicles per hr per lane.

Figure 4 shows the 4-mi stretch of the pacer system in four 1-mi sections from 11 Mile to 15 Mile. The equipment of the traffic pacer system is located as indicated by the symbols. In all, there are 43 speed signals and 11 pre-intersection stop signals. Details of the pacer system hardware are contained in the Appendix.

EXPERIMENTAL DESIGN FOR TRAFFIC PACER TESTING PROGRAM

There are two types of traffic systems that are in existence on today's signalized arteries. The most common system is the noninterconnected system in which no definite phase relationship exists between successive intersection signals. The non-interconnected system is referred to as the past system. By adding the interconnection feature, the traffic engineer can establish the proper phasing of the succeeding intersection signals, which is coincident with the particular speed between a pair of intersections. This system is popularly known as the progressive system. By adding the properly phased speed signals and the presignals to the progressive system, one creates a traffic pacer system.

Figure 1 shows pacer control elements in operation. To alert the motorist of the experimental test area, roadside signs like those in Figure 5 were installed beyond each intersection. Portions of this sign were blanked out for the progressive and past systems as shown in Figure 6. A roadside sign was placed at the extremities of the system informing the motorist that he was leaving the experimental test area. Speed

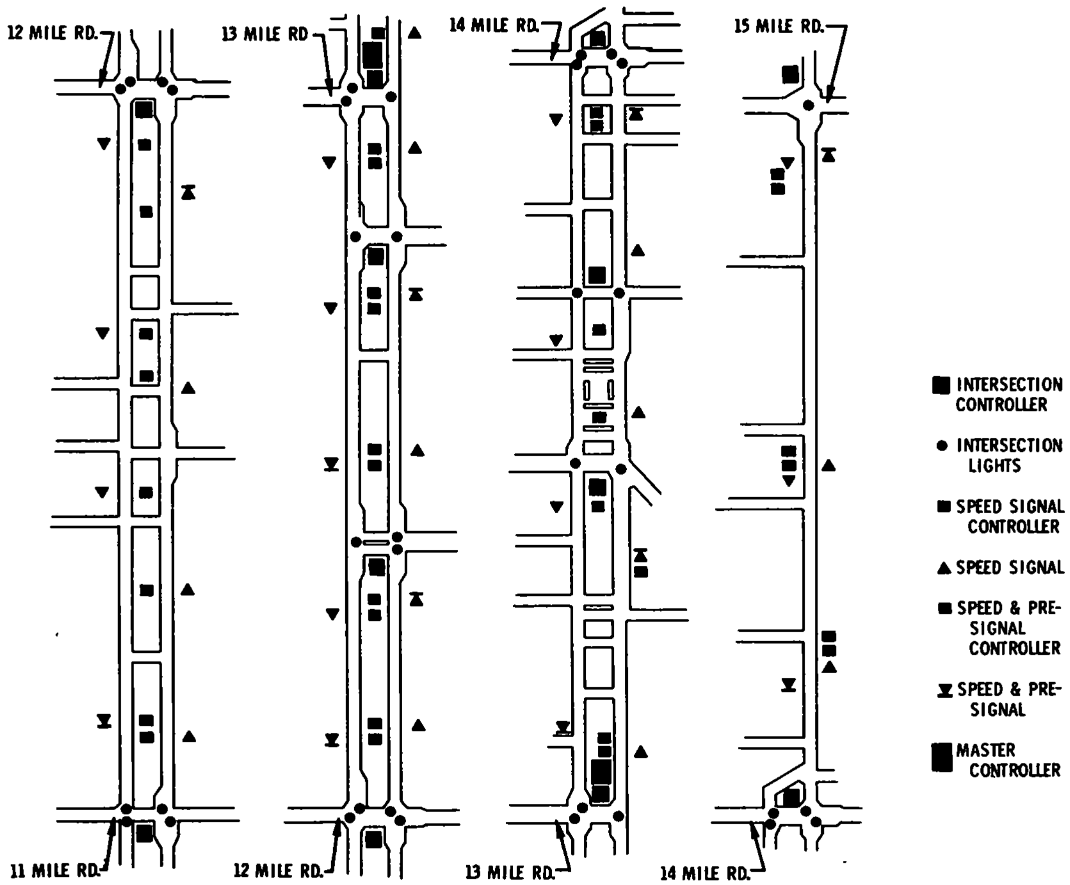


Figure 4. Location of traffic pacer equipment.

signals and presignals were blanked and bagged, respectively, for the operation of the progressive and past systems, as in Figure 7. "Signals Set At" signs were placed above the normal speed limit signs, as in Figure 8, to indicate the progression speed and were removed for the past system. It was a fortuitous circumstance that the progression speed for a 60-sec cycle turned out to be exactly the same as the speed limits that have recently existed on Mound Road.

A comparison of these three traffic systems (past, progressive, and pacer) was the object of the first 12-week testing program. The following performance criteria were used:

1. Average trip time, average velocities, and average number of stops.
2. Intersection capacity.
3. Queue length.
4. Safety.
5. Public opinion.
6. Possible driver economies.

Four professional data takers were provided by the Michigan State Highway Department for the initial 12-week testing program. Trip time and number of stops were recorded by the data takers while driving Mound Road between 11 and 15 Mile Roads. The data takers drove as an "Average Driver" passing about as many cars as passed them. Traffic counts were taken of the number of cars passing an intersection during the green portion of the light cycle. Queues (number of cars waiting for signal) were also recorded at the intersection, and in the case of the pacer system, at the pre-signal, during the red portion of the cycle. Accident reports and radar checks were recorded by the Warren Police Department during the testing program and compared with previous records. Public acceptance of the pacer system as well as the other two systems was measured by distributing questionnaries to motorists traveling on Mound Road. Also, a small number of fuel economy data were taken.

Figure 5. Roadside sign informing motorist of experimental test area.

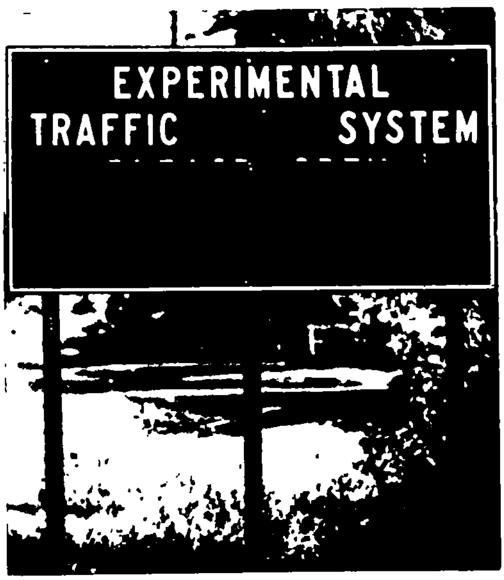


Figure 6. Roadside sign legend with progressive and past systems.

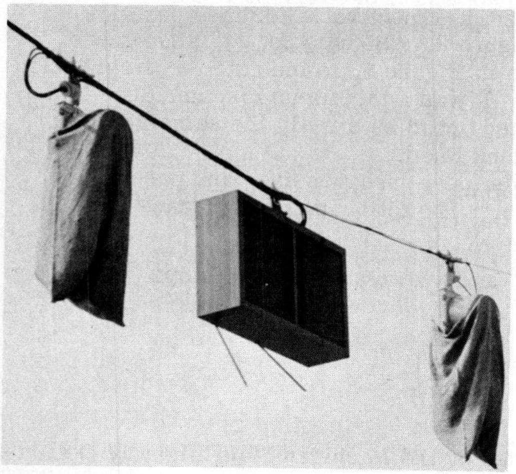


Figure 7. Speed and presignal for progressive and past systems.

Figure 8. Progressive system speed sign.

Procedure

So that weather and any other environmental variables would not affect one system more than another, a balanced design for testing was used. Due to certain time and scheduling restrictions, a completely balanced design could not be used. The three systems (A, pacer system; B, progressive system; C, past system) appeared in the following order during the 12-week testing program: C, A, B, C, B, A, C, A, B, C, B, A. During the experimental testing period, all other traffic control parameters were held constant, such as cycle length, split, offset, and speed limit. The testing periods used were 6:30 to 9:00 AM and 3:00 to 5:30 PM, Monday through Friday. These two time periods included the heaviest volume of traffic each day. System changes were made on each Saturday by the Macomb County Road Commission. Data were taken at the following intersections: 12 Mile and Mound, north and south bound; 13 Mile and Mound, north and south bound; Chicago Road and Mound, north and south bound; 14 Mile and Mound, north and south bound; 15 Mile and Mound, north bound; and 11 Mile and Mound, south bound. An equal number of observations were made at each intersection for all systems. Traffic counts at all intersections were also balanced for time of testing and day of the week in an incomplete randomized block design. For example, data were taken at the same intersection, the same four days of the week, at the same time intervals for all three systems. This was done to eliminate any effect day-to-day variability might have on the results. Randomization and replication are paramount for interpretation of the results of this experiment in any objective sense. The most important assumption concerning this experiment is that the traffic volume not change over the entire testing program.

Due to road construction, system failures and decreased traffic volume during the auto company-union strikes in the area, approximately one week of data were not usable for each of the three systems tested.

Instrumentation and Data Processing

The following instruments were used to collect data on traffic:

1. A portapunch unit, which holds a preperforated IBM card. A stylus was used to punch the number of cars that went through the intersection.

2. A productograph, which records the time of day to 0.1 sec when the operator depresses a button. This instrument was driven from a car battery by a 12-v DC to 110-v AC converter. It was used by the driver of the trip time car to record the time that he had passed an intersection light—accuracy ± 2 sec in 8 min.

3. A fuel metering instrument used to obtain fuel consumption data from the pace car. It uses two calibrated burettes for measuring the amount of fuel that was used in traveling the 4-mi experimental test section—accuracy 0.1 percent.

Pictures of these data-taking instruments are in the Appendix. Figure 9 shows how these instruments were used in each of the data-processing systems.

RESULTS

Consistency Measures

The assumption was made earlier that the traffic volume not change appreciably from the onset to the end of testing. Traffic counts at all intersections were compared on a weekly basis, and no significant change was noted throughout the testing program. The average standard deviations for the total number of cars through an intersection, the number of cars turning right and the number of cars turning left were ± 7, ± 12, and ± 10 percent, respectively. In other words, the actual number of cars through, right, and left differed from the average by less than these amounts 67 percent of the time. The number of cars through each intersection was totaled for each system. The percentages of the total traffic volume for the three systems are as follows: pacer system, 33.8 percent; progressive system, 33.2 percent; and past system, 33.0 percent. Figures 10 and 11 show the traffic flow patterns for the 4-mi experimental testing area during the morning and evening rush periods.

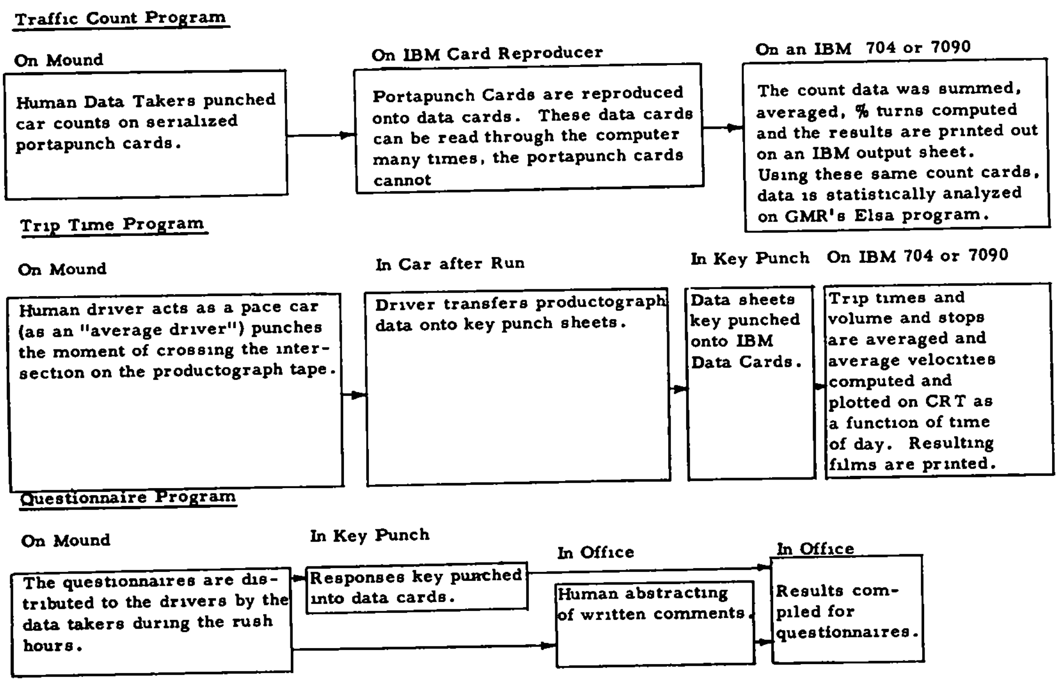


Figure 9. Flow chart of data-processing systems employed for traffic pacer 12-week comparison study with progressive and past systems.

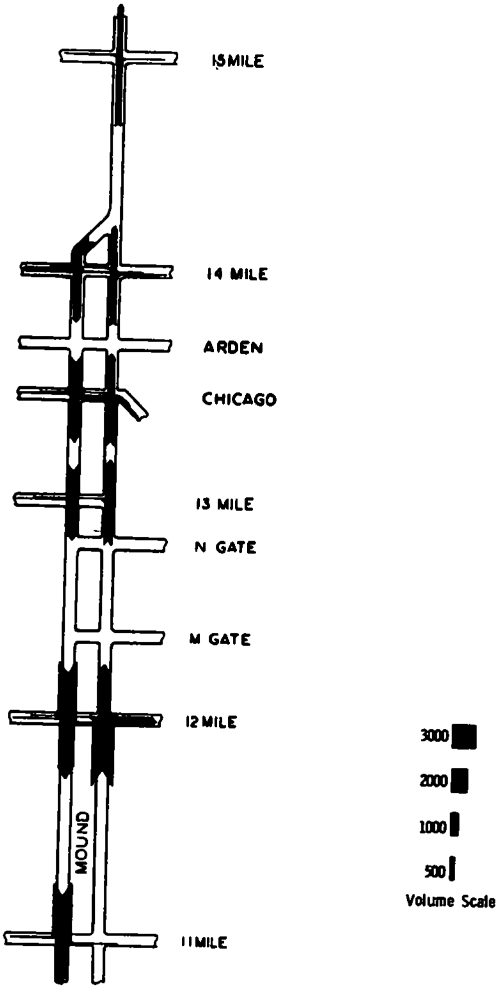


Figure 10. Average traffic volume for 12-week testing period, 6:30 to 9:00 AM.

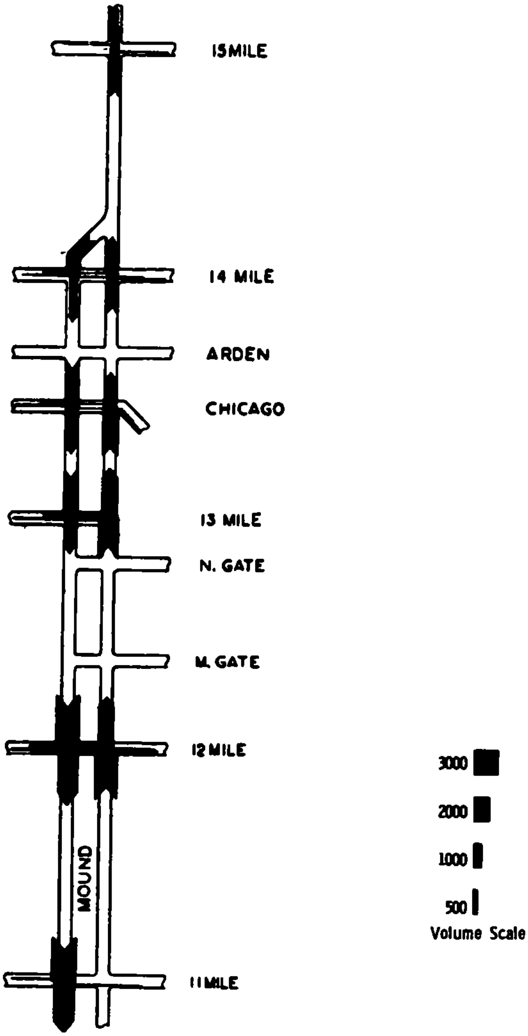


Figure 11. Average traffic volume for 12-week testing period, 3:00 to 5:30 PM.

Trip Times

Frequency of Stops. — While actual trip time data were being taken, the number of complete stops per trip was also recorded. The average number of stops per trip for morning and evening traffic is given in Table 1. A trip is defined as traveling from 11 to 15 Mile Road or 15 to 11 Mile Road, a distance of 4 mi with 8 intersection signals.

The greater number of average stops in the evening is attributable to an increase in the traffic volume. How many miles a motorist can travel before he has to make a complete stop under the three systems is given in Table 2.

An analysis of variance was performed on these data, and the systems were found to be significantly different beyond the 0.05 level of confidence.

Stops may also be thought of as a delay to the driver in traveling from one place to another with a certain amount of displeasure associated with each delay. If one assumes one-half the red cycle as the average delay per stop and compares the three systems on the time delay per trip (4 mi), the results are given in Table 3.

Table 3 only includes the theoretical average time that a car is stopped and does not include the time lost in deceleration or acceleration before and after a stop. Although the average delays are not large, the displeasure associated with them is probably much greater, especially for manually shifted automobiles and trucks.

Continuous records were made of the time taken to travel the 4-mi experimental test area. Average velocities were computed from the time recores and are given in Table 4.

Trip time was significantly less for the pacer and progressive systems when compared with the past system (t's obtained were significant beyond 0.01 level of confidence). No statistically significant differences were found between the pacer and progressive systems. This result is to be expected because even in periods of very light traffic the trip time will be determined by the progression speed which was the same for both pacer and progressive systems; that is, with either of these systems a driver operating above the progression speed would be stopped at some intersection signal and slowed to progression speed.

The frequency of stop data indicates that the additional information given the driver by the pacer system permits more accurate speed control and avoids stops as frequent as those observed with a progressive system.

The questionnaire results indicate that drivers feel they are making better time when driving the pacer than either of the other systems. This might suggest that the driver's judgment of time is in-

TABLE 1

AVERAGE NUMBER OF STOPS PER TRIP

System	Avg. No. of Stops	
	AM	PM
Pacer	0.23	0.73
Progressive	0.41	1.17
Past	2.35	3.20

TABLE 2

AVERAGE NUMBER OF MILES TRAVELED BEFORE STOP

System	Avg. No. of Miles Traveled	
	AM	PM
Pacer	17.24	5.46
Progressive	9.71	3.41
Past	1.70	1.25

TABLE 3

TIME DELAY

System	Delay (sec/trip)	
	AM	PM
Pacer	3.45	10.95
Progressive	6.15	17.55
Past	35.25	48.00

TABLE 4

AVERAGE TRIP TIME AND AVERAGE VELOCITY

System	AM			PM		
	Average Trip Time			Average Trip Time		
	Sec.	Std. Dev. Conf. Interval	Avg. Velocity (mph)	Sec.	Std. Dev. Conf. Interval	Avg. Velocity (mph)
Pacer	401.6	±24.3[a]	36.6	428.4	±41.7	34.3
Progressive	398.4	±23.9	36.9	432.7	±48.3	33.9
Past	463.8	±41.2	31.6	482.9	±46.3	30.4

[a]One standard deviation confidence interval.

fluenced more by the amount of time that the vehicle is stopped than by the time the vehicle is in motion.

Some typical plots obtained from the trip time computer program are shown in Figure 12.

Queue Length

A summary was made of the average number of cars queued per cycle at each intersection for the three systems. These averages were then totaled, and a comparison was made between the average number of cars queued per cycle for all the intersections at which data were taken on all three systems. In the case of the pacer system, the number of cars queued per cycle was recorded at both the intersection and at the presignal (see Table 5).

From the standpoint of traffic control, vehicles stopped at a presignal are of less concern than those at an intersection. The greater fraction of green time permits vehicles to accelerate to road speed before the intersection is reached and they do not delay cars behind them.

A t-test was performed on the average queue length at the intersection for the pacer vs progressive, pacer vs past, and progressive vs past system. The average queue length observed under the pacer

TABLE 5

AVERAGE NUMBER OF CARS QUEUED PER CYCLE FOR ALL INTERSECTIONS

System	Cars Queued (Avg. No.)	
	At Intersection	At Intersection and Presignal
Pacer	0.80	3.58
Progressive	4.99	
Past	6.28	

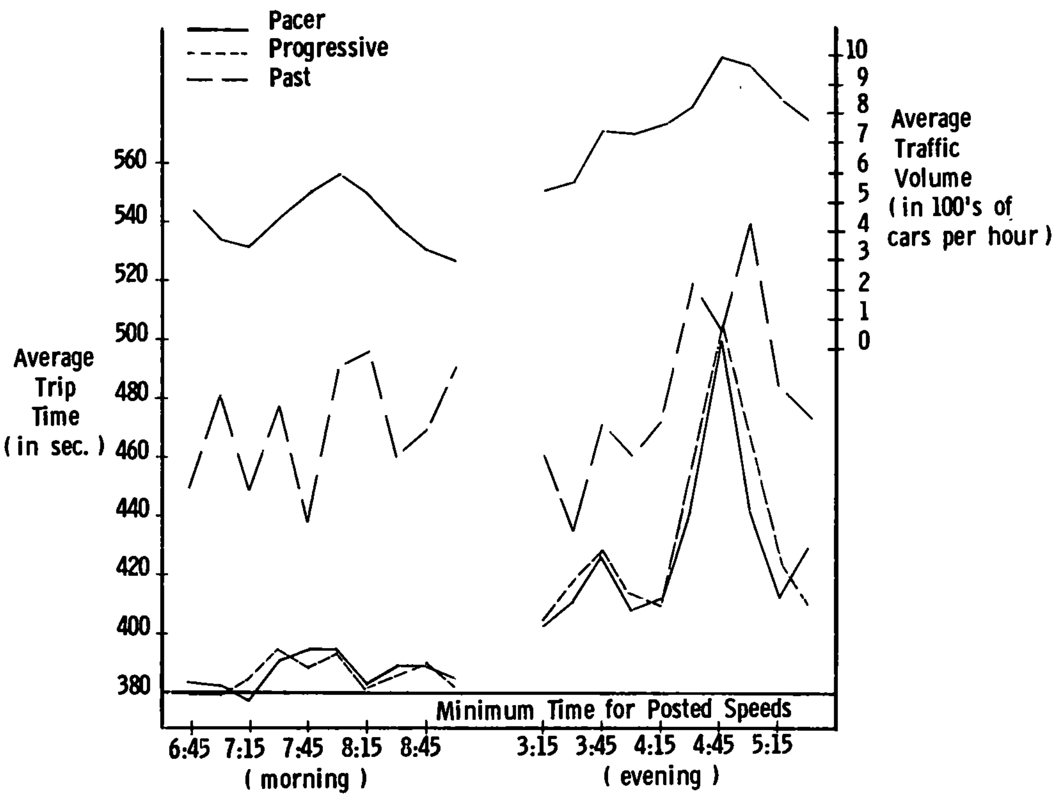


Figure 12. Trip time vs time of day for northbound traffic.

system was significantly less than that with either the progressive or past systems (both beyond 0.01 level of confidence). The average queue observed with the progressive system was not significantly different from that using the past system. After combining the queues at the intersection and at the presignal, the difference between the pacer system and progressive system was significant at the 0.08 level of confidence, and the difference between the pacer and past systems was significant at the 0.02 level.

It was further hypothesized that some relationship might exist between traffic density and queue length (the average number of cars queued at an intersection during the red portion of the cycle). Figure 13 shows this relationship for the three systems. A linear least squares fit, in the general form $y = mx + k$, was performed on the data for traffic up to and including 1,200 cars per hr. Data beyond this point were fit visually. The standard error of estimate (σ_W), which is a measure of goodness of fit, for the straight line fit to the pacer data was $\sigma_W = 0.063$.

The standard error of estimate for the pacer including queues at the presignal was $\sigma_W = 0.259$ and values of $\sigma_W = 0.231$ and $\sigma_W = 0.253$ were obtained for the progressive and past systems, respectively.

A certain amount of error was involved in judging the length of a queue. However, the error is quite small, in the neighborhood of ± 1 car for 15 cars queued and ± 3 cars for 25 cars queued. All counts of 40 or more queues were given the value of 40. Because each data taker counted at the same intersection for each of the three systems, the amount of judgment error should not differ appreciably between the systems.

Intersection Capacity

From the beginning of the 12-week testing period, the authors realized that there

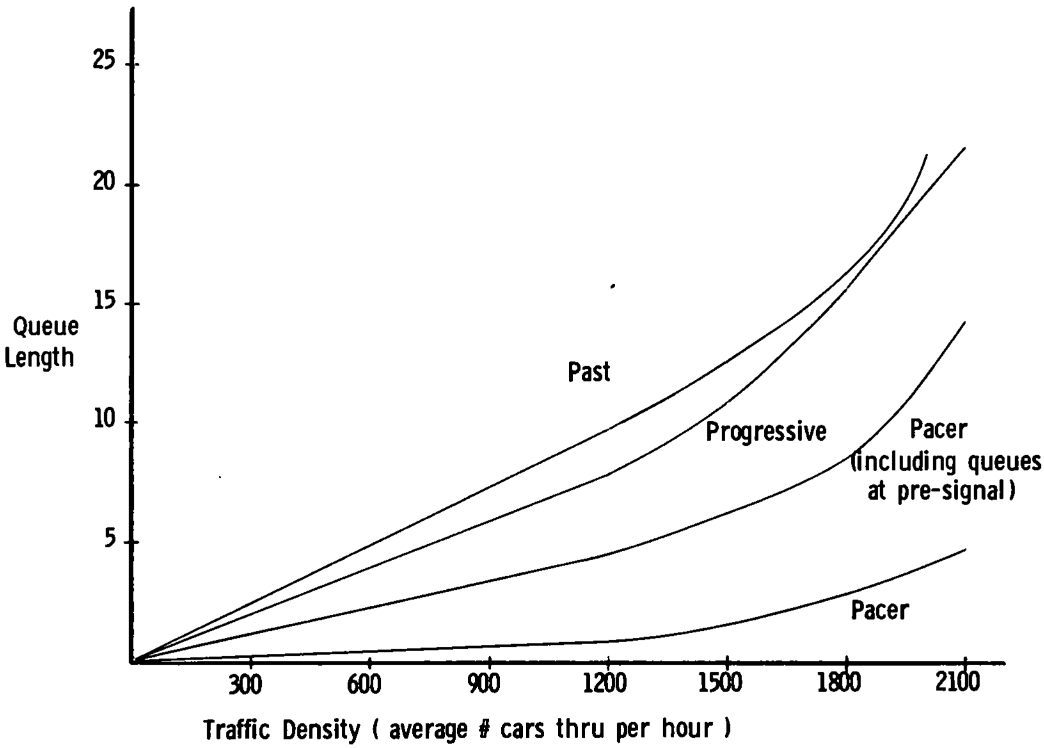


Figure 13. Queue length vs traffic density.

are many variables that might influence the maximum number of cars that can pass through an intersection. These parameters are for all traffic systems as follows:

1. The length of the green phase.
2. The length of the amber phase.
3. The percentage of turns.
4. The length of the turn aprons.
5. The local speed limit.
6. The percentage of trucks in traffic; that is, the average accelerations (plus or minus) and length of the vehicles.
7. The time phasing of the arrival of cars from the last intersection.
8. The sight distances available to the driver as he approaches the intersection.
9. The clarity of signing near the intersection.
10. The time of day.
11. The width of the lanes.
12. The proximity of parked cars.

For the pacer system there are several other parameters:

1. The distance from the presignal to the intersection.
2. The time phasing of the release of drivers from the presignal to the intersection.
3. The time phasings of all speeds shown on all the speed signals with respect to the intersection signal.
4. The time durations of all speeds shown on all speed signals preceding each intersection.
5. The use or the absence of the flashing high speed at the presignal just before the onset of the presignal amber.
6. The actual speeds to be shown on the speed signals.

In the 12-week experiment, the variables for all traffic systems were held constant except 3 and 6, which were monitored for consistency. From one week in which the pacer was operating, to the next week that the pacer was in operation, all the variables for this system were kept constant. Although these six parameters were set by theoretical calculation to be the best for that location, there are undoubtedly some of these initial settings that should be changed to obtain the maximum capacity at each intersection. For example, the distances to the intersection from the presignal were intentionally made different in an attempt to establish the best operational distance. Only a small improvement was expected in capacity. Theoretically, von Stein has predicted an increase of two cars per cycle per lane attributable to the presignals. However, small increases in capacity are worth a great deal when one considers the cost required to obtain an equivalent increase in capacity through the purchase of additional right-of-way and the use of additional concrete.

In an attempt to ascertain any over-all improvement in intersection capacity, all the heavy volume intersections at rush periods were compared by measuring the frequency of cycles in which some arbitrary maximum car count per cycle or over made it through the intersection during the green. For example, at an intersection during the rush period, the number of times that 30 or more cars got through during the green portion of the cycle was recorded. The results are given in Table 6.

TABLE 6

AVERAGE PERCENT OF LIGHT CYCLES DURING WHICH 30 OR MORE CARS PASSED THROUGH AN AVERAGE INTERSECTION

System	Light Cycle (%)
Pacer	25.4
Progressive	19.4
Past	17.1

The 8.3 percent improvement of the pacer over the past system was statistically significant beyond the 0.01 level of confidence. The pacer's 6 percent improvement over the progressive system was significant at the 0.05 level. No significant difference was obtained between the progressive and past systems.

Results from Questionnaires

Another comparison was made between the three experimental systems in the form of a questionnaire. A total of 600 questionnaires were distributed by the State data takers each week. The questionnaires were distributed to drivers entering or leaving the experimental test area of 11 to 15 Mile Roads. In order that a true taxpayer's evaluation might be made, the questionnaires were mailed to the Macomb County Road Commission. Each week the drivers were asked to compare the system in operation that week with the system in operation the preceding week. An explanation of each of the three systems under test and the two systems that were to be compared accompanied each questionnaire. A copy of the questionnaire used is in the Appendix. Approximately 1,800 questionnaires were not distributed because of system malfunctions, road construction, and other factors beyond control. A total of 6,000 questionnaires were distributed and 1,350 or 22.5 percent were returned. A basic assumption, as mentioned earlier, is that traffic volume does not change appreciably over the 12-week testing period. To make valid comparisons between the three systems, all other external variables should remain as consistent as possible. To test for consistency, various responses to the questionnaires were analyzed.

Drivers indicated whether they were driving a truck or an automobile, what time of day, how often, and how many miles they normally traveled on the experimental system from 11 to 15 Mile Roads. No statistically significant differences were observed from week to week during the 12-week testing program for responses to all the information listed. In other words, the ratio of cars to trucks remained stable, the distribution of trip lengths and frequencies of travel per week did not change, and the time distribution of traffic also remained constant. Table 7 gives the average frequencies of the listed traffic information.

TABLE 7

QUESTIONNAIRE QUESTIONS AND ANSWERS

Question	Answer: Category	Answer: Percent
What type of vehicle are you driving?	Auto	95.7
	Truck	4.2
	NR	0.1
How often do you normally travel on Mound Road? (times per week)	5 or more	88.3
	2 to 4	8.6
	1 or less	2.7
	NR	0.4
How many miles do you normally travel each morning or evening on Mound Road between the experimental test area of 11 and 15 Mile Road? (mi)	Less than 1	7.2
	1	20.2
	2	20.7
	3	16.5
	4	35.4
At what time interval do you usually travel on Mound Road?[a]	Rush hours (6-9 AM; 3-6 PM)	92.8
	Midday (9AM-3PM)	15.1
	Evening (After 6PM)	21.2

[a]Summation of percentages of response greater than 100 percent due to multiple responses.

As mentioned earlier, the traffic volume and percentage of turns were very consistent over the 12-week testing period. The consistency measures obtained from the questionnaires give further support to the important basic assumption, that the amount and type of traffic remain constant throughout the testing program.

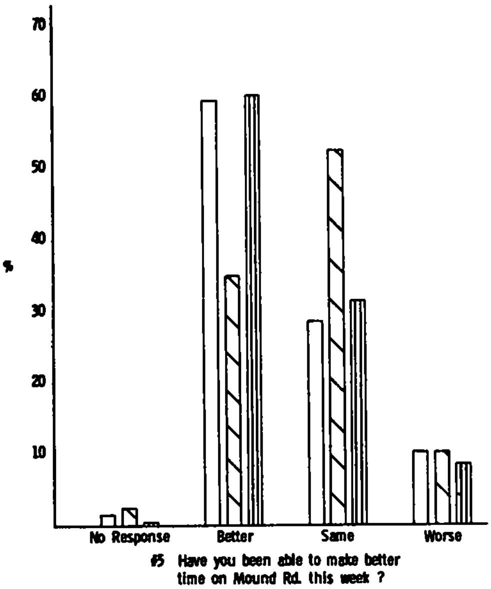


Figure 14.

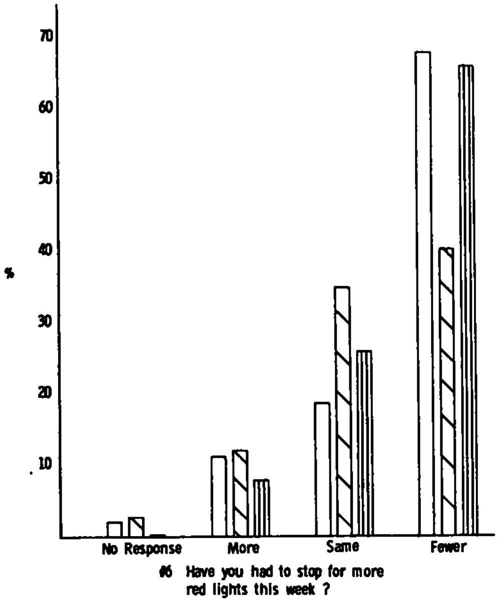
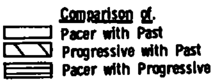


Figure 15.



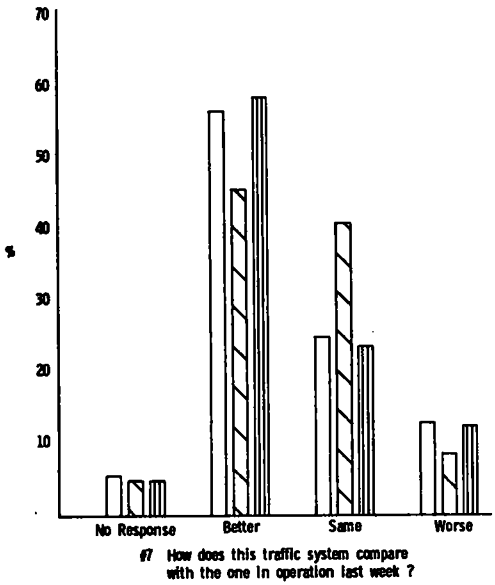


Figure 16.

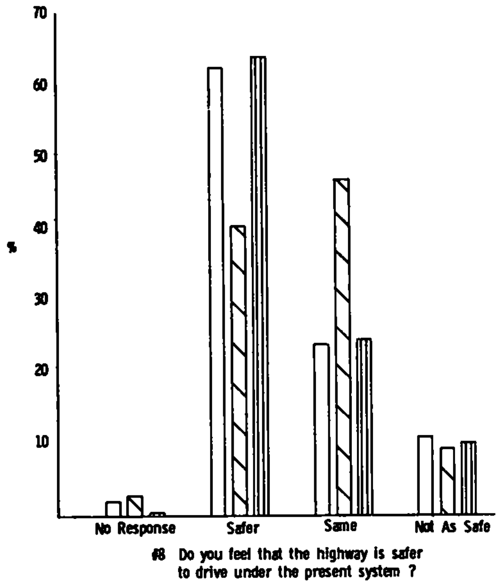


Figure 17.

Basic Comparisons

Responses to questions 5, 6, 7, and 8 are shown in Figures 14 to 17. Each system was compared with the other two systems, and in all cases the pacer system was preferred to either the progressive or past systems. The pacer system was preferred significantly more to the past system than was the progressive system to the past system. However, no significant difference was obtained when comparing the pacer with both the progressive and the past systems; i.e., the pacer system was preferred as much to the progressive system as it was to the past system.

The statistic used to test for differences between the three systems was χ^2. This measures discrepancies between observed and theoretical frequencies and makes probability statements about these discrepancies. The confidence level (probability level) chosen was 0.05. This means that the value of χ^2 obtained from any difference between observed and theoretical frequencies must be high enough so that it could have occurred by chance only 5 times out of 100 occurrences. Whenever a significant difference is noted in the report, it is so beyond the 0.05 level of confidence.

The χ^2 obtained for the comparisons between the pacer-past systems and progressive-past systems on questions 5, 6, and 8 were all significant beyond the 0.01 level of confidence. For question 7 the χ^2 was significant at the 0.055 level of confidence.

In general, the drivers preferred the pacer system to the other systems, felt that they were making better time, fewer stops, and that driving was safer.

No problems were noted concerning the legibility of the overhead speed signs. When motorists were asked if they had trouble maintaining the indicated speeds on the overhead speed sign, approximately ⅓ of them stated that they did have trouble. Of these, about 30 percent said the signs changed too often and too rapidly, suggesting an incomplete understanding of the operation of the system. The responses to what point they should be going the suggested speed with respect to the overhead speed sign (question 11) indicated that over 50 percent of the drivers were following the signs as soon as they could see them or were not sure where to begin the suggested speed, even though the legend under each speed sign read, "Begin Through Speed Here." Of those drivers who had trouble maintaining the speed on the overhead speed sign, about 30 percent stated that other drivers were not cooperating in following the suggested speeds. Another 25 percent gave as their reasons slow moving vehicles, heavy traffic, and cars turning onto cross-streets from Mound Road. Again, these percentages did not change significantly from the start of testing to the end of testing.

When the drivers were asked if they would like to see the pacer system installed on other roads, 74.5 percent said "yes," 20.4 said "no," and 5.1 gave no response. The attitude of the drivers to this question did not change significantly from the first week of testing to the last week of testing as indicated in Table 8.

TABLE 8

ANSWERS TO QUESTION ON APPROVAL OF PACER SYSTEM INSTALLATION ON OTHER ROADS

Week	Response (percent)		
	None	Yes	No
Second	8.2	74.9	16.9
Sixth	7.7	75.4	16.9
Eighth	3.6	71.4	25.0
Twelfth	1.1	76.1	22.8

The main reason for not wanting the pacer system installed on other roads was that it would increase taxes. As mentioned earlier, the questionnaires were mailed to the Macomb County Road Commission. The drivers possibly thought that the Commission was paying for the installation, and hence the County was undertaking an experimental project with taxpayers' money. The other reasons for not wanting other installations varied from preferring the progressive system to not liking the presignals to being a distracting influence from the driving task.

A comparison was made between truck drivers' and auto drivers' opinions concerning the pacer system. Approximately the same percentage of truck drivers had trouble maintaining the indicated speed as did the auto drivers. There were no significant differences between the truck and auto drivers' opinions concerning installation of the pacer system on other roads. Questions 5, 6, 7, and 8 were combined and responses were listed in the categories favorable, neutral, or unfavorable. Results for the auto-truck comparison are shown in Figure 18. Truck drivers prefer the pacer to the past system significantly more than do auto drivers. Both auto and truck drivers prefer the pacer system to the progressive system about equally (no statistically significant difference). However, auto drivers significantly prefer the progressive system to the past system more than do the truck drivers. This last finding may be due to the importance that truck drivers ascribe to the presignals, possibly indicated by their significantly greater preference for the pacer system over the past system. The pre-

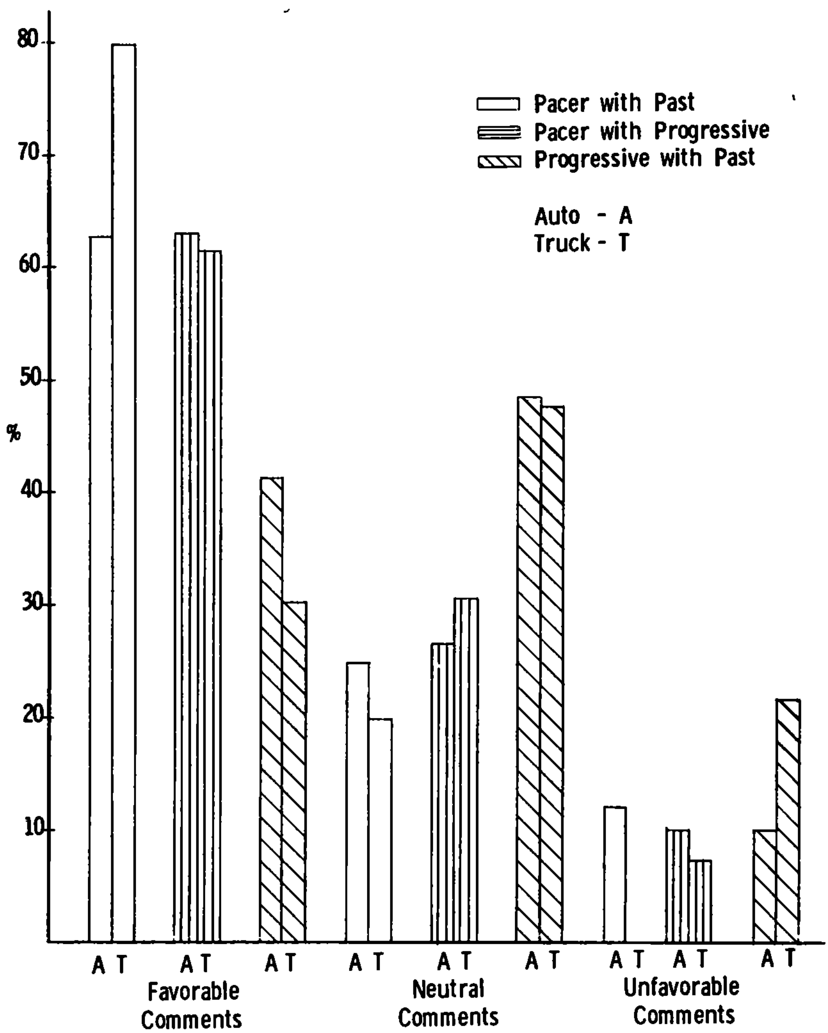


Figure 18. Comparisons among systems.

signals give the truck driver a chance to pick up speed so he can be moving when the intersection light turns green. If a truck driver is stopped while traveling on the progressive system, this advantage is lost.

In any type of public opinion research, it may be asked how different the results would have been if everyone had been questioned and not just a sample from the total population driving on Mound Road. By computing the sampling tolerance at the 0.95 confidence level, it was found that for observed percentages of 50 percent, the results would not change more than ± 3.57 percent and for percentages in the neighborhood of 10 or 90 percent the results would not change more than ± 2.14 percent if all Mound Road drivers had been questioned.

User Economies

Because drivers make fewer stops using the pacer system, and because a great deal of gasoline is consumed in accelerating, it might be expected that vehicles driven on the pacer system should experience better fuel consumption. To test this hypothesis in an abbreviated experiment, one driver was selected to drive the pace car three successive mornings on the three different traffic systems. The vehicle used was a 1961 passenger car. The temperature outside on the three days was $55^0 \pm 5^0$ and the fuel temperature was $75^0 \pm 5^0$ for the three days of the test. The trips were made both north and south to cancel out the effects of wind. Table 9 shows the results of this abbreviated test.

The transitive nature of the data is immediately apparent; i.e., there is an increasing improvement as one observes the data in the order past, progressive, and pacer. However, because of the small number of observations, the only observed statistical difference was between the pacer and past systems for mean fuel consumption.

Although it has not been tested, it might be expected that brake wear should also be significantly reduced by the pacer system because of the fewer stops that the drivers are encountering.

Safety

Possibly the only true criteria for safety is number of accidents. Because accidents are such relatively rare events, a true estimate of safety would take much more time than the four weeks in which the pacer system was operating. On the other hand, some inferences can be made about safety. Because the pacer creates large gaps in the traffic stream, entering a busy artery from a nonsignalized cross-street is easier to accomplish. Also, at busy pedestrian intersections, a vehicle-pedestrian accident should be less likely to occur if the vehicles stop at the distant presignal. From the measures of queue length, the pacer system reduced the average number of cars waiting at an intersection by 87 percent over the past system and by 84 percent over the progressive system. Because fewer cars are waiting at an intersection, the chance for intersection accidents may be reduced. As was pointed out in the questionnaire results (see Fig. 17), 64 percent of the motorists thought that the pacer was safer than either the past or progressive systems, 24 percent thought that the pacer was about the same as the other two systems, and only 11 percent thought that the pacer was not as safe.

From verbal reports of the drivers of the experimental pace car and from observations made by the Warren Police Department, it was felt that fewer lane changes were being made. This may be attributable to no advantage being gained by going over the speed limit and passing other cars. Radar checks were made before and after the installation of the pacer system and although the average speed of traffic was only slightly slower, the variability of automobile speeds was greatly reduced when the pacer system was in operation. The 85th percentile speed before installation of the pacer system was 47.5 mph and was reduced to 44.7 mph after the installation. This means that traffic was more uniform and that speeding was not as prevalent. No accidents were attributable to system changes.

TABLE 9

COMPARISON OF FUEL CONSUMPTION FOR THE THREE SYSTEMS

System	No. of Runs	Relative Fuel Consumed (pacer = 1.0)	Avg. Time of Trips (sec)	Avg. No. of Stops per 4 Mi	Date, Day, and Time
Pacer	6	1.00	414.7	0.333	10/20/61 Friday a.m.
Progressive	9	1.05	424.2	0.667	10/23/61 Monday a.m.
Past	8	1.12	440.8	1.88	10/24/61 Tuesday a.m.

Future Testing of Pacer System

In the next twelve months, a variety of experiments will be conducted in two main areas: capacity and system simplification. The system will be refined to meet the specific needs of the Mound Road test area. Additional data will be taken on the same performance criteria and compared with the results of the present experiment.

SUMMARY AND CONCLUSIONS

Results from the initial 12-week testing program comparing the three systems (A, traffic pacer system; B, progressive interconnected system; and C, noninterconnected system) are as follows: Traffic volume was constant over the entire testing period. Significantly fewer stops were made under system A, higher average speeds could be maintained, and trip times were less for systems A and B than for system C. The intersection capacity was increased, inasmuch as high volume traffic counts on an average were 8.3 percent more frequent for A than C and 6 percent more frequent than B. The average number of cars queued under system A was 44 percent less than system C and 27 percent less than B. System A had equivalent safety, and results from the questionnaires indicated that approximately 65 percent of the people felt that A was safer and faster, and caused fewer stops than B or C. Also, 75 percent of the respondents would like to see system A installed on other roads.

Future research will be conducted so that capacity and system simplification may be explored to a greater extent.

ACKNOWLEDGMENTS

The authors wish to thank the members of the Macomb County Road Commission for their continual cooperative spirit and diligent work in the construction and maintenance of the pacer system and, in particular, their assistant engineer, Warren Anderson. They express their thanks also to the Michigan State Highway Department, whose Research Group, headed by Edward Gervais, supplied guidance in the Pacer design and whose Survey Group, headed by Julius Negri, supplied the data-taking personnel. At the General Motors Research Laboratories, there were many contributors to the success of the project: Herbert Bauer for his design of the speed signal, Fred Becker and Norman Brainard for their help in the electrical design of the system, James Dallemand for his statistical assistance, George Cole for his comprehensive "trip time" program, and to Joseph Bidwell for his continuing interest and direction of the project. Also, they express their thanks to the Detroit Edison Company and the Michigan Bell Telephone Company for their continuing cooperative spirit and assistance in the design and installation of the traffic pacer system. The Warren Police are also to be thanked for their cooperation in reporting accidents and speed checks through the direction of Inspector Charles Rabideau.

REFERENCE

1. Herman, R.C., "Theory of Traffic Flow." Elsevier (1961).

Appendix

TRAFFIC PACER HARDWARE

For purposes of testing the traffic pacer control concept, the pacer hardware was designed and installed to be flexible. The specifications for the traffic pacer speed signal equipment called for the following:

1. Six independently selected cycle lengths.
2. Five independently selected offsets.
3. Four independently selected splits and number sequences (the split and number sequences are tied together).

In general, each speed signal or speed and presignal had its own controller. The controllers were mounted on a pole in pairs of double cabinets, one double cabinet for the northbound direction and one double cabinet for the southbound direction, as shown in Figure 19. This dual controller arrangement allowed for independent selection of the northbound and southbound speed number sequence. If two speed signals had been operated from one controller, a split or offset change could cause a lighting sequence change, requiring nonstandard equipment to be built. Hence, the single controller per speed signal resulted in a more flexible design. When the testing period is over, the lighting sequence can be frozen, and any sequence changes that result from offset or split changes can be resolved in favor of the best compromise. In fact, it would be possible, and much less expensive, to operate the speed signal from the intersection controller.

The pacer system was designed to be fail safe. In each intersection controller, a timer terminates the cross-street green with a pre-emptive cross-street amber, if the camshaft does not index ahead to the cross-street amber position when actuated by the dial key. The entire traffic pacer system is interconnected with telephone lines.

Figure 20 shows in schematic form the fail safe circuitry that ties the pacer system intersection controllers together. If the contacts are broken in any of the locations A, B, or C (intersection controllers), all the local controllers are switched to local Edison power from the power that had been supplied the intersection controller by the local amplifier. The local amplifier supplies a voltage to the controller synchronous drive motor, the frequency of which is slaved to the frequency of the master. It is the output of the local intersection amplifier that holds in a fail safe relay, the contacts of which are used to complete the series circuit. Thus, if any of the intersection controllers were to stop running on master frequency, this event would be detected, and the local failed intersection would continue servicing traffic on a 60-sec cycle obtained from local intersection power. If this situation were to occur, the speed signals adjacent to the failed intersection would not be in phase with the failed intersection. Hence, the master control sends a shut-down function to all the speed signals and establishes the presignals in an amber flashing condition. If the failure occurred at a speed signal or presignal and not at an intersection, the local speed signal would be blanked and the presignal would establish an amber flashing condition. Figure 21 shows the master control for the pacer system.

The speed signal used in the pacer system is a multibulb signal, with small relays used to perform the switching of the numerals in the signal. Figure 22 shows a close-

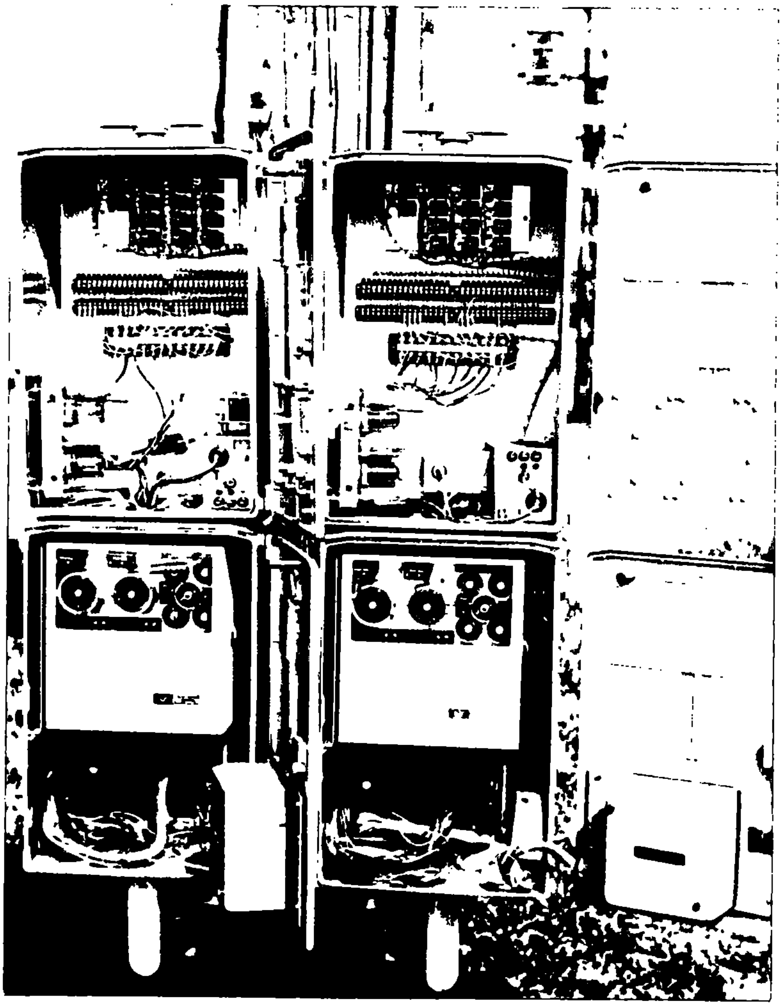


Figure 19. Typical mounting of speed signal controller double cabinets. Conventional controller contained in lower cabinet, and terminal strips for wiring speed number sequence contained in upper cabinet. Right cabinet pair controls northbound speed signal; left cabinet pair controls southbound speed and presignal.

up view of the front of the speed signal, and Figure 23 shows the front "Koolshade" screen lowered and one of the digits removed, and turned to show the relays. The relays are mounted in about a 2-cps natural frequency suspension system to avoid the sharp high frequency vibrations in the horizontal direction created by the actuation and release of the relays. Such high frequency vibrations were fatiguing the bulb filaments. These small relays only switch the numerals displayed after the controller has broken the power. The power in the local controller is not applied to the new numeral configuration until the small relays in the speed signal are changed to thier new configuration. General Motors report 350 contains a discussion on the actual bulbs lit for each numeral and the clarity of the signal under various lighting conditions.

NOTES:

1. A, B and C are contacts on failure alarm relays with each local controller.
2. Current relay senses breaks in fail-safe line and open-failure alarm contacts.
3. Voltage relay senses shorts on fail-safe line.

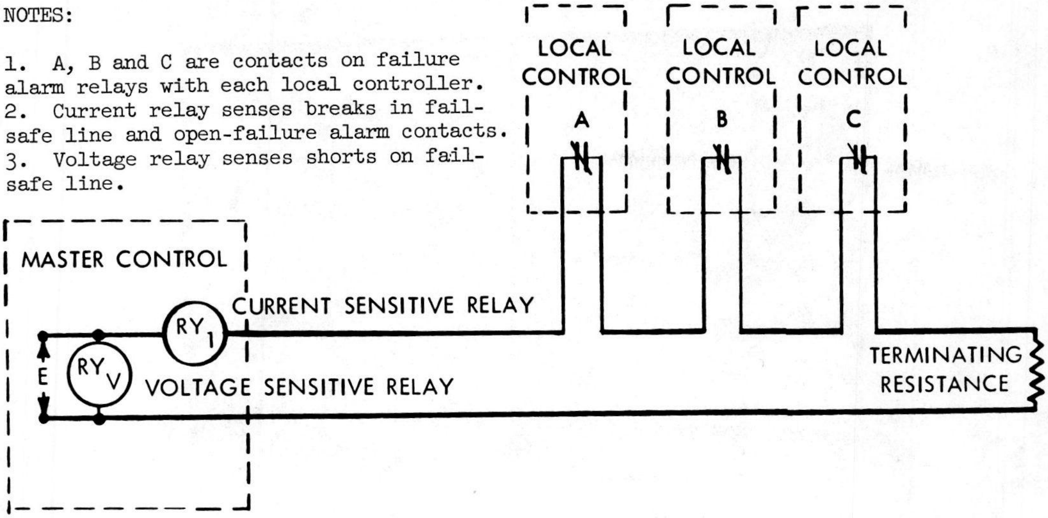


Figure 20. Failure alarm circuit.

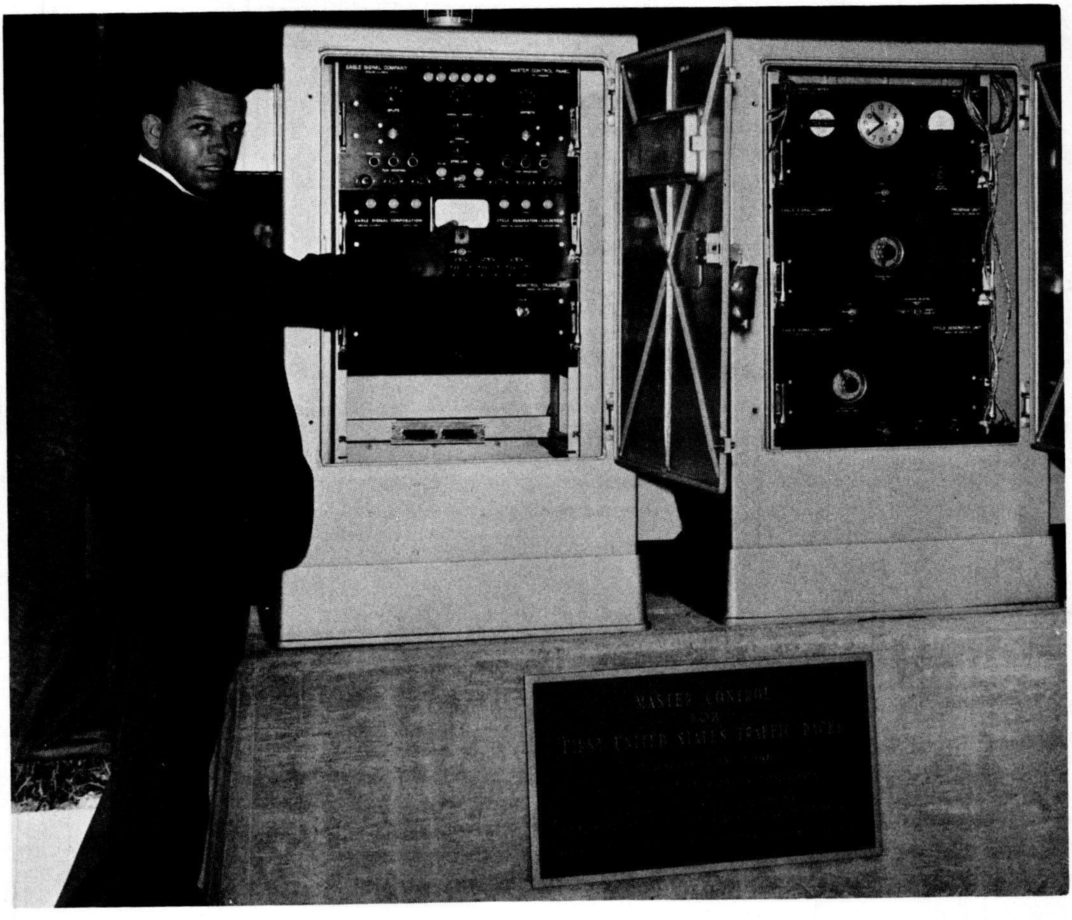


Figure 21. Pacer system master control.

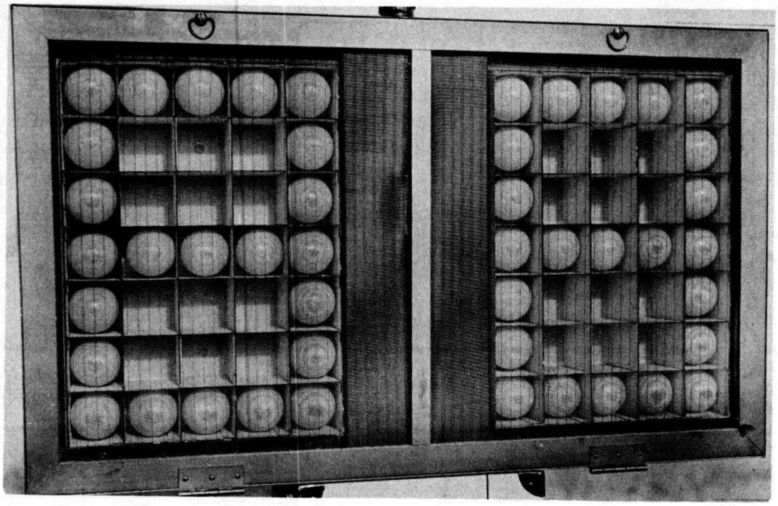


Figure 22. Close-up of speed signal.

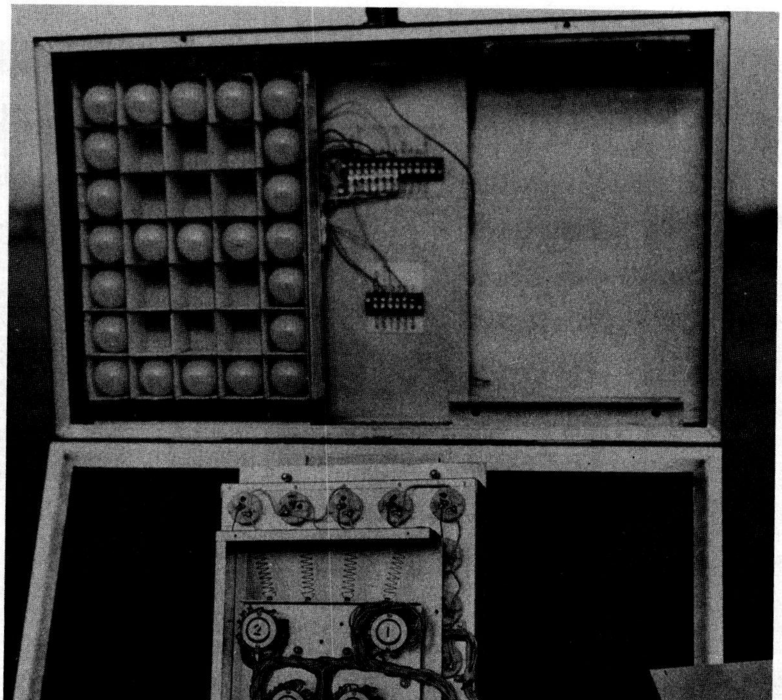


Figure 23. Close-up of interior of speed signal with right digit removed to show switching relays and their suspension.

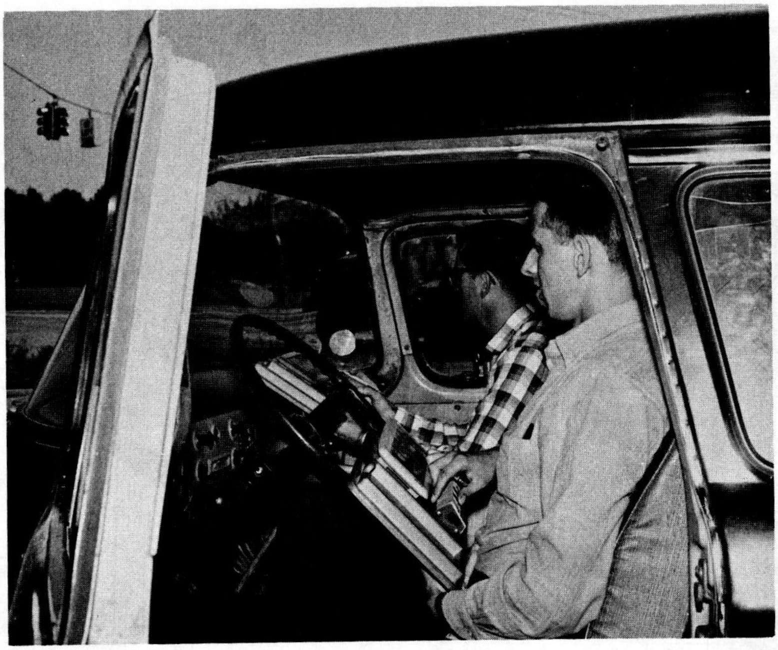


Figure 24. Operation of portapunch unit.

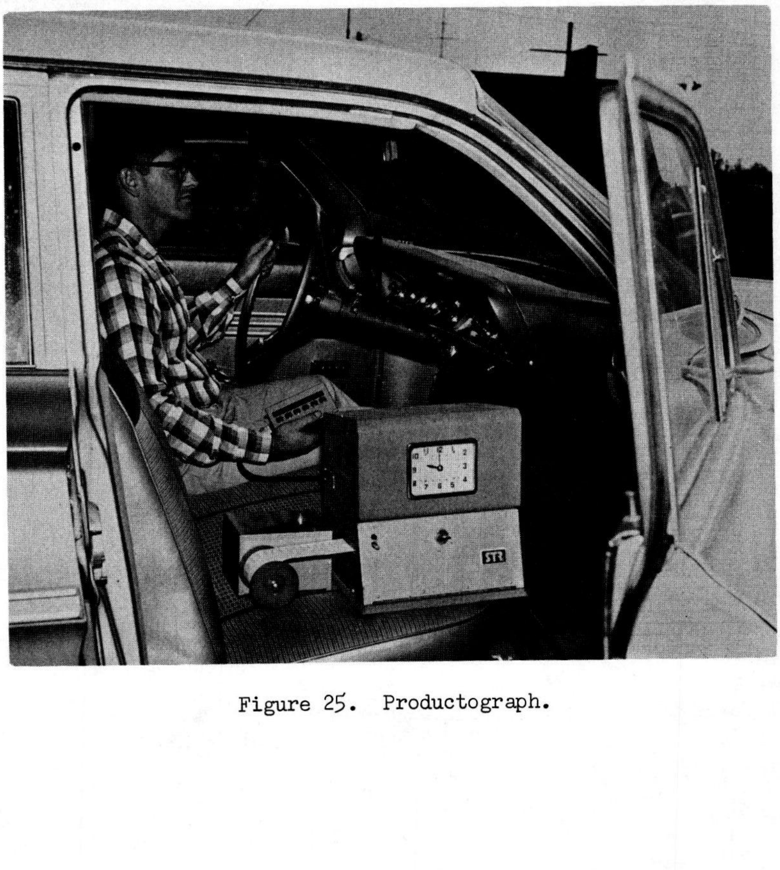


Figure 25. Productograph.

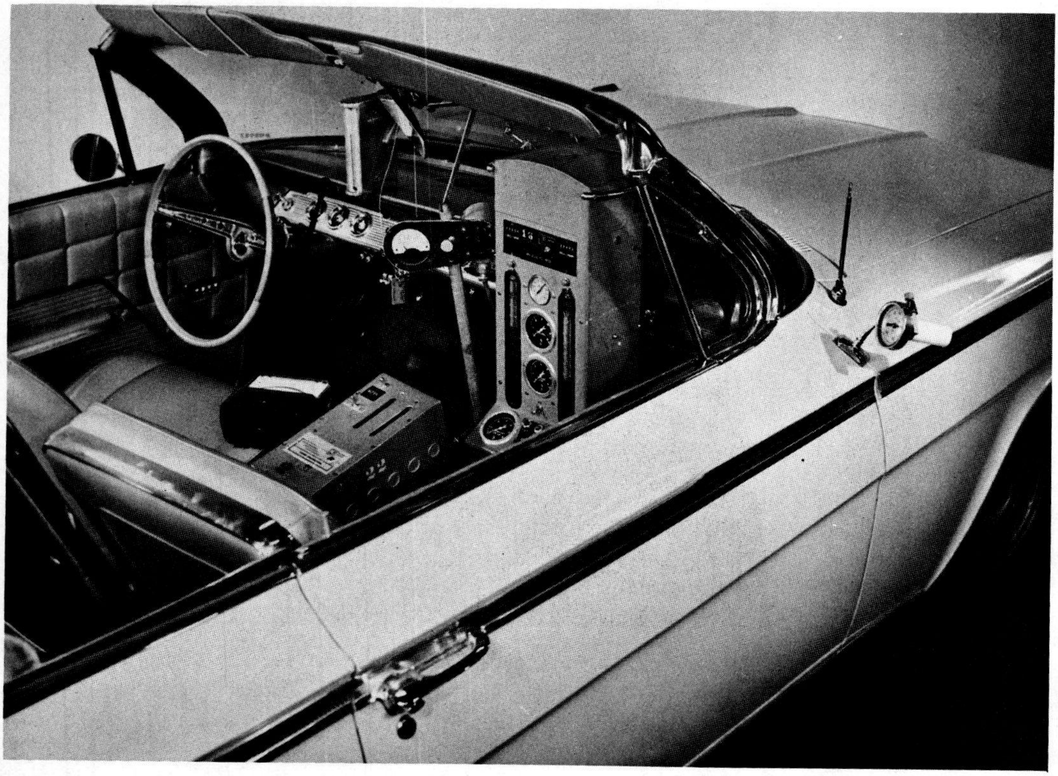


Figure 26. Fuel meter.

SAMPLE QUESTIONNAIRE

Three different traffic control systems are being tested on Mound Road between Eleven and Fifteen Mile Roads.

THE ORDINARY SYSTEM

The system used on most of the highways and streets.

THE PROGRESSIVE SYSTEM

The system in which the traffic signals are set at the posted speed.

THE PACER SYSTEM

The system in which overhead speed signs indicate the speed to travel in order to make the next traffic signal.

The system in operation this week is the____________________.
The system in operation last week was the ________________________.
Please compare these two systems by answering the questionnaire provided.

How many miles do you normally travel each morning or evening on Mound Road between the experimental test area of 11 Mile Road to 15 Mile Road?

LESS THAN 1 MILE____ 1 MILE____ 2 MILES____ 3 MILES____ 4 MILES____

Please return this sheet with the questionnaire provided.

PLEASE DISREGARD IF YOU HAVE ALREADY
FILLED OUT A QUESTIONNAIRE THIS WEEK

We would be very interested in your opinions of the experimental traffic systems being tested on Mound Road between 11 and 15 Mile Roads. Please answer the questions below and return them in the postage-free envelope as soon as possible.

THANK YOU

1. Have you ever filled out a similar questionnaire on the traffic system in use this week?

   YES____ NO____

2. What type of vehicle are you driving?

   AUTO____ TRUCK____

3. How often do you normally travel on Mound Road?

   5 OR MORE TIMES/WEEK____ 2--4 TIMES/WEEK____

   ONCE OR LESS/WEEK____

4. At what time intervals do you usually travel on Mound Road?

   6--9 AM____ 9 AM--3 PM____ 3--6 PM____

   AFTER 6 PM____

5. Have you been able to make better time on Mound Road, within the experimental test area of 11 to 15 Mile Road, this week? (________________to________________) *

   BETTER____ ABOUT THE SAME____ WORSE____

6. Have you had to stop for more red lights this week? (____________ to______________) *

   MORE____ ABOUT THE SAME____ FEWER____

7. How does this traffic signal system compare with the one in operation last week? (______________to______________) *

   BETTER____ ABOUT THE SAME____ WORSE____

8. Do you feel that the highway is safer to drive under the present system?

   SAFER____ SAME AS BEFORE____ NOT AS SAFE____

* The actual week of system test was specified in the ( ).

*
9. Do you have any trouble reading the overhead traffic speed sign?

YES____ NO____ If YES, please explain.

10. Do you have any trouble maintaining the indicated speed on the changing overhead speed sign?

YES____ NO____ If YES, please explain.

11. At what point with respect to the overhead speed sign do you feel you should be going the suggested speed?

12. Would you like to see other main roads equipped with the present Traffic Pacer System?

YES____ NO____ If NO, please explain.

13. Do you have any comments or suggestions about the traffic signal system in use this week on Mound Road?

THANK YOU FOR YOUR COOPERATION

*Questions 9, 10, 11, and 12 were not included on the questionnaires the weeks in which the Progressive and Past Systems were in operation.

Discussion

H. J. KLAR, Chief Traffic Engineer, New Jersey Bureau of Traffic Safety, Trenton—Although the authors' efforts to increase the traffic capacity of a signalized intersection are commendable, the writer would like to raise a few questions.

1. Is the rear-end collision potential being increased by funneling vehicles through the main intersection at very close spacings?
2. Is the number of accidents increased when the accidents at both the main intersection and the presignalized location are added?
3. Will the obedience to traffic signals be lessened by the introduction of the presignal at a nonintersection (midblock) location?
4. Could not large compliance by motorists be obtained if the proper speed of progression were continuously displayed, thereby avoiding the possible negative aspects of questions 2 and 3?

In a brief verbal discussion with one of the authors he indicated that, though the posted speed limit was 40 mph, the 85 percentile speeds measured approximated 48 mph. If this is so, the writer believes this information should have been presented with the paper because it is a strong indication why motorists did not realize and hence did not react favorably when the signals were offset for a progressive movement at 40 mph. In other words, their normal operating speeds were higher than the speed of the signal progression and hence they were slowed or stopped by red signals in most instances and did not feel that the signals were in progression.

In the writer's work, establishment of the speed of progression as close as possible to the 80 to 90 percentile speed of traffic regardless of the speed limit has been attempted. In this way, it has been possible in many instances to get the speed limit raised so that it more nearly fits traffic conditions.

Intersection Traffic Control Through Coordination of Approach Speed

S. M. BREUNING, Associate Professor of Civil Engineering, Michigan State University, East Lansing

• VARIATION of approach speed promises considerable improvement in traffic control at signalized intersections. It can be accomplished by means ranging from complex speed control signal systems to simple roadside signs. The aim of these controls is to improve the smoothness and efficiency of intersection operation and, even more importantly, to move the driver through the intersection with ease.

The need for improving the flow of traffic at signalized intersections is as old as the traffic signal itself. The arbitrary alternation of complete blockage and free flow at the intersection brings with it two severe driver objections. One grows out of the uncertainty and anxiety of the approaching driver towards the end of the green phase, when he worries whether the light will change on him and require sudden stopping. The other is a combination of irritation at being stopped and impatience at the length of the stop.

Approach speed control can keep the traffic moving at all times. If properly designed, it can replace the stop-and-go alternations along the highway with fluctuations in the speed of flow. This creates flow concentrations, which mesh with similar flow concentrations on the cross-route, thus alternating the use of the intersection by the crossing routes without stopping the flow. This system eliminates stopping at the intersection on the highway and so obviates the anxiety about a sudden light change.

A discussion of the principles and theories of controlling approach speed and a description of a low-cost application, together with a discussion of the fundamentals of the well-known traffic pacer, outline the possibilities of this type of control.

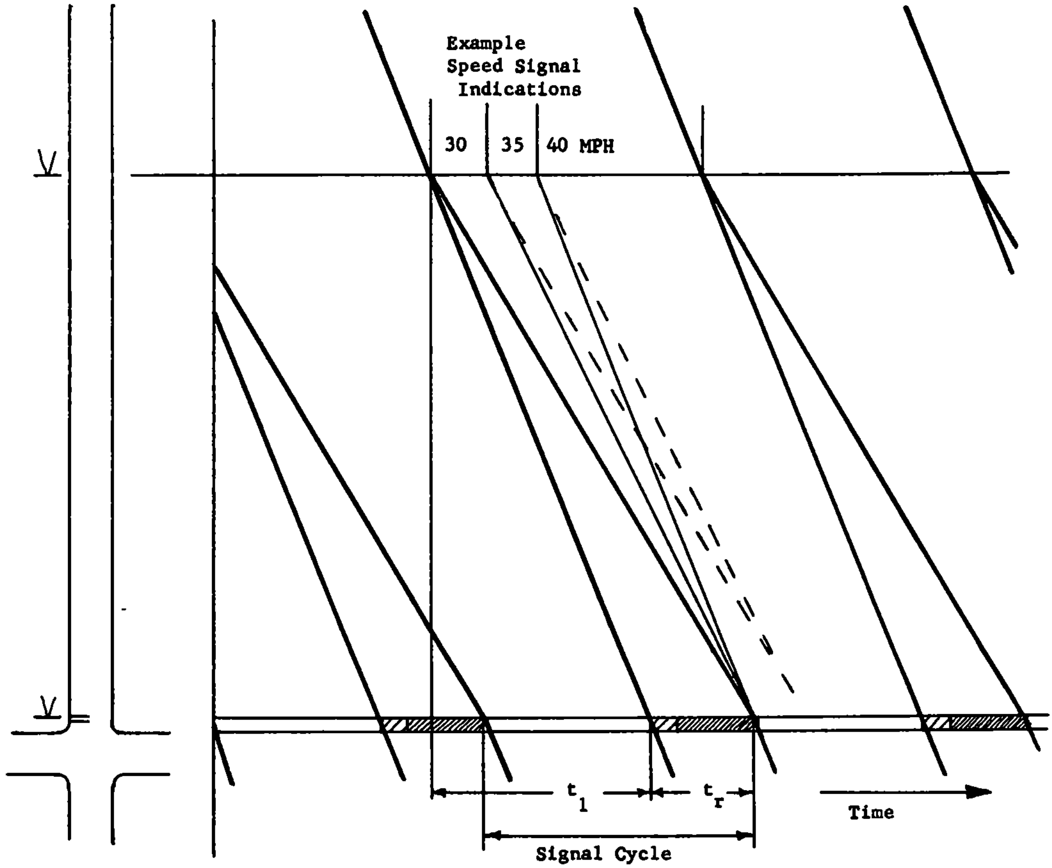
TRAFFIC FUNNEL THROUGH APPROACH SPEED CONTROL

A funnel is a cone used for pouring things into narrow-mouthed containers. A traffic funnel "pours" vehicles, originally spaced at random along a highway, into the narrow time period of the green phase at an intersection.

Operation of the Traffic Funnel

Figure 1 shows the principle of a traffic funnel on a time-distance graph, familiar to everyone who has worked on signal timing. The "funneling" of the traffic approaching the intersection is accomplished by reducing the speed of a group of vehicles passing a given point on the highway ahead of the intersection during a given time period, while the speed of the succeeding group is reduced somewhat less, and so forth, until the last group passing the given point maintains its free speed. While moving through the funnel, a platoon is gradually built up behind the vehicles that have been slowed, until all vehicles are closely spaced so that they all reach the intersection during the green phase. None need be stopped.

The motorist approaching the intersection encounters at a considerable distance (in the order of several thousand feet) ahead of the intersection a speed signal that indicates at what speed he should proceed. If he follows the recommended speed he will be funneled to reach the intersection while the signal is green. The recommended speed at the approach signal varies between the free-flow speed of the traffic (or the speed limit of that roadway) and a reduced speed of about $\frac{3}{4}$ to $\frac{2}{3}$ of the free flow speed, so that a comparatively minor modification will guarantee arrival at the intersection during the green phase.



t_r = Amber + Red Phase Time

t_1 = Approach Time at Free Speed

Figure 1. Components of approach speed control.

Advantages of the Traffic Funnel

In its ideal form approach speed control not only minimizes interference with the free passage of the individual automobile driver, but also increases the capacity of the intersection through compression of the vehicle platoon in the funnel and through the reduction of acceleration losses at the beginning of the green phase. A better safety record may also be expected through elimination of the unexpected change of light. Savings in time, gasoline, mechanical wear, accident damage and drivers' emotional energy are all possible with a well-designed system of approach speed control.

COMPARISON WITH OTHER CONCEPTS OF INTERSECTION CONTROL

A review of other methods of controlling traffic at intersections and of their characteristics in use will demonstrate the conceptual difference that underlies the principle of controlling approach speed.

The Intersection

An intersection is a piece of real estate belonging simultaneously to two or more crossing routes. In this definition "simultaneously" obviously presents the aspect that creates a problem. Any attempt by the users of two intersecting routes to use the intersection simultaneously leads to undesirable results. Consequently, controls or design changes have been developed to eliminate the simultaneous use of the intersection roadway by two or more routes.

The most obvious solution, but usually a prohibitively expensive one, is to remove the intersection by providing roadway surfaces above or below each other on the same piece of real estate. This provides uninterrupted right-of-way to each route.

Basic Right-of-Way Rule

The basic rule, on any intersection not otherwise controlled, provides a right-of-way preference only in the case of conflict, but then arbitrarily assigns it to the vehicle on the right. This rule works well only for light traffic on intersecting routes of the same type.

Stop or Yield Control

This type of control gives preference at all times to one route over others and permits the use of the intersection roadway by the secondary routes only when there is no possible conflict with users on the primary route. It works well until the traffic on the major route approaches continuous flow or the volume on the secondary routes increases sufficiently that delays become excessive.

Signal Control

The traffic signal assigns the right-of-way on the intersection to the intersecting streets alternatively or in rotation. The use of the intersection is always given completely to one road and denied completely to the other routes. Consequently, traffic on the intersecting streets either is completely stopped or is allowed to flow completely unimpeded (although the later drivers must worry about the possible change of the signal light indication).

This method of control always delays about one-half of the traffic using the intersection and therefore should be used only when the other methods of control are sure not to work.

Approach Speed Control

This control is applied at the approaches to an intersection by funneling the traffic flow on each route into the green phase, and thereby clearing each route of any traffic at the intersection during its red phase, while cross-route traffic is being accommodated. Thus approach speed control works by concentrating and intermeshing the crossing traffic streams.

This type of control is a modification of the method of assigning the use of the intersection exclusively to one of the intersecting streets in turn. But complete and abrupt blockage never occurs and therefore this control system does not interfere severely with the traffic flow.

This system would seem to be applicable to every traffic signal to which it can be fitted. Moreover, because it does not generate the same objections as a traffic signal, it might find application in many locations where traffic signals alone have not been considered desirable before.

COMPUTATION OF TRAFFIC FUNNEL

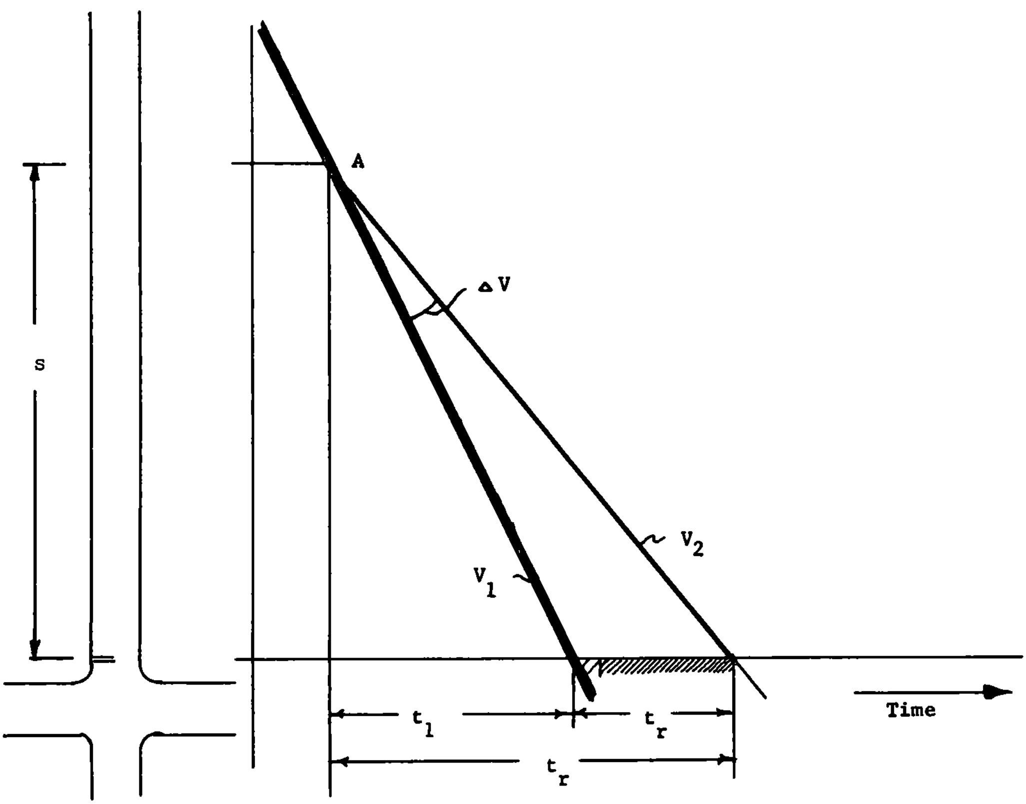
For simplicity, an intersection of only two routes is used in this discussion.

Time Gap

Because the funneling process at a signalized intersection must be repeated for every signal cycle, it is somewhat easier for computation to consider the time gap that is created between the last car of the first funnel and the first car of the following funnel. This time gap increases towards the intersection and at the intersection must be as long as the red phase of the signal. Figure 2 shows how a "time gap triangle" is formed on the time-distance diagram between the last potential vehicle traveling at free flow speed V_1, the first potential vehicle at the slow speed V_2, and the time of red and amber phase t_r.

Definitions

V_1 = free flow speed,
V_2 = slow approach speed,



$$s = 1.47\, t_r V_1 \left[\frac{V_1}{\Delta V} - 1 \right]$$

$$t_1 = \frac{s}{V_1} = 1.47\, t_r \left[\frac{V_1}{\Delta V} - 1 \right]$$

Figure 2. Development of traffic funnel.

ΔV = $V_1 - V_2$; approach speed difference,
s = approach distance, or length of traffic funnel,
t_1 = approach time, or travel time through funnel at free flow speed,
t_2 = approach time at slow approach speed, and
t_r = red phase at signal (including amber).

Computation

With these components the characteristics of and the interrelationships within the funnel can now be computed. It may be assumed that normally the free flow speed of traffic V_1, the duration of the green phase at the intersection t_r, and one of the remaining three variables are known. If the speed difference is given or assumed, approach distance, s, and approach time t_1 can be computed to define point A, which determines both the distance ahead of the intersection where the speed control signal must be installed, and the timing of that signal in relation to the timing of the intersection signal.

From the basic speed equations,

$$V_1 = \frac{s}{t_1} \text{ (fps) and } V_2 = \frac{s}{t_1 + t_2} \text{ (fps)} \tag{1}$$

$$V_1 = \frac{s}{1.47\, t_1} \text{ (mph)} \qquad V_2 = \frac{s}{1.47\,(t_1 + t_r)} \text{ (mph)} \tag{2}$$

Solving for t_r,

$$t_r = \frac{s}{1.47\, V_2} - \frac{s}{1.47\, V_1} = \frac{s\,(V_1 - V_2)}{1.47\, V_1\, V_2} \tag{3}$$

and substituting $\Delta V = V_1 - V_2$,

$$t_r = \frac{s}{1.47}\; \frac{\Delta V}{V_1\,(V_1 - \Delta V)}$$

Solving for s,

$$s = 1.47\, t_r\, V_1 \left(\frac{V_1}{\Delta V} - 1\right) \tag{4}$$

$$\frac{s}{t_r} = 1.47\, V_1 \left(\frac{V_1}{\Delta V} - 1\right) \tag{5}$$

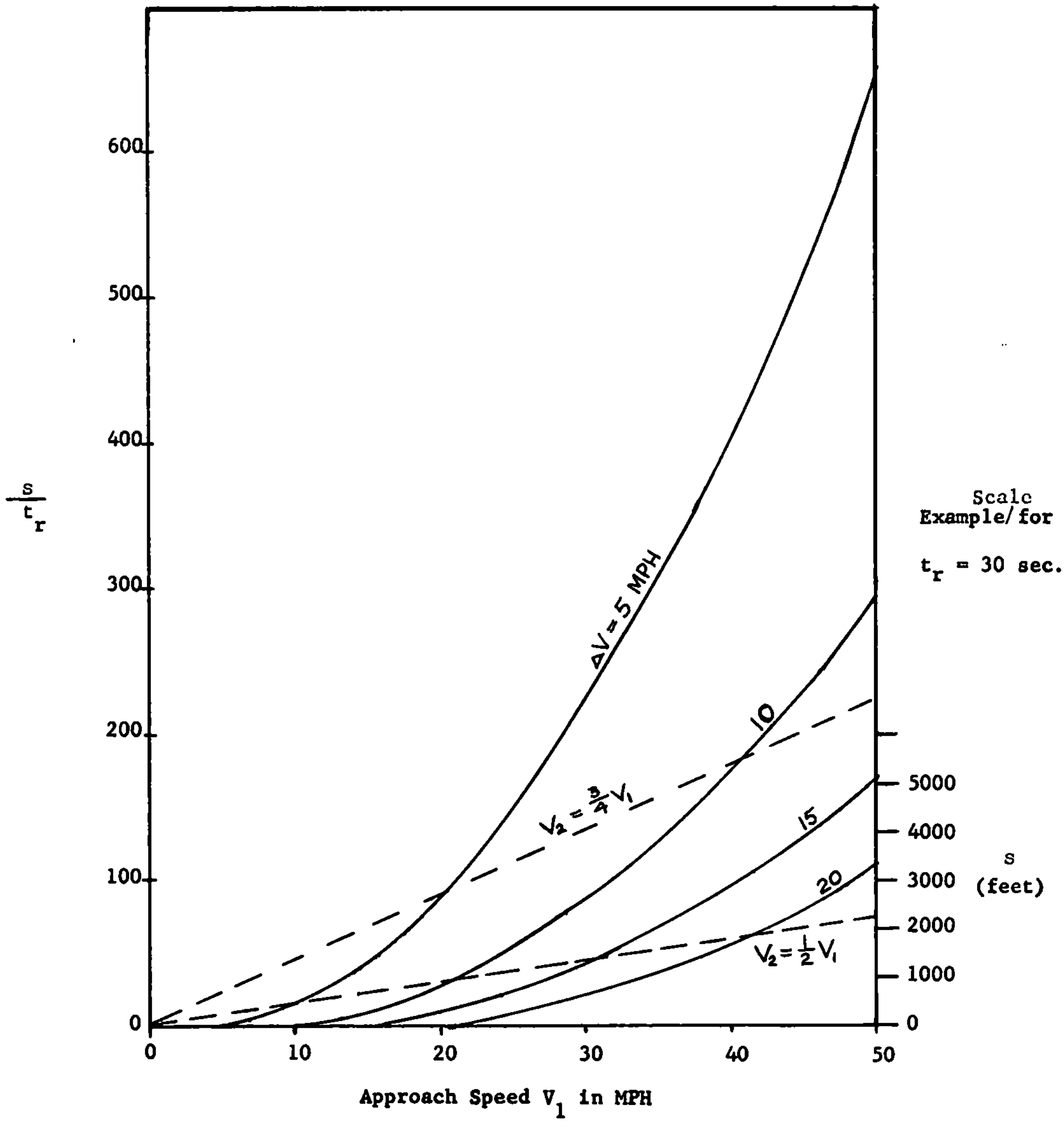
and for t_1,

$$t_1 = \frac{s}{V_1} = 1.47\, t_r \left(\frac{V_1}{\Delta V} - 1\right) \tag{6}$$

Eq. 4 shows that the approach distance increases with the square of the free flow speed. It also increases linearly with the duration of the red phase and decreases with an increase in speed difference. As a consequence, rather long approach distances are necessary for high-speed intersections.

A chart showing the range of s as a function of free flow speed and speed difference is given in Figure 3. The vertical scale is s/t_r, which might be considered the "unit approach length." It is the length in feet required for each second of red phase duration. The use of this scale makes the data in this chart almost universally applicable. As an example of actual approach length requirements, the distance for 30-sec red phase duration is also given.

The chart shows plainly the excessive approach lengths required for high free flow speed and low speed differences. This will require careful compromising in selecting the most advantageous values for actual applications.



$\frac{s}{t_r}$ = Unit Approach Length per Second of Red Phase

s = Approach Length in Feet

Figure 3. Approach length chart.

Introduction of the speed difference as a fixed fraction (1/n) of the free flow speed would yield an equation linear in V_1. From Eq. 4 and $\Delta V = \frac{1}{n} V_1$,

$$s = 1.47\, t_r\, V_1 (n - 1) \tag{7}$$

or

$$\frac{s}{t_r} = 1.47\, V_1 (n - 1) \tag{8}$$

which is a straight line from the origin. For example, the required distance for speed reductions by one-quarter and one-half are shown dashed in the graph. Eq. 7 or 8 will not be used here, because each expresses a relative speed reduction by a given fraction and not the absolute speed reduction, which governs the action of the motorist. A speed reduction of 10 mph requires almost as much action from the motorist and takes almost as long at 50 mph as at 25 mph.

Accuracy

There are three sources of difference when these theoretical computations are compared with data from actual field installations: (a) variability of point where driver responds to the speed signal, (b) variation in pattern of actual speed change, and (c) inaccuracy of speed indication on automobile speedometers.

Location of Driver Reaction

The performance of approach speed control depends first of all, but probably not mostly, on the time and place where the driver will react to the message given him by the approach speed control signal. It will vary widely between the driver encountering this control for the first time and traveling past the signal before comprehending and reacting to its message, and the driver traveling this route slowly and responding to each sign whenever he can first read its message.

Most installations will probably be used primarily by repeating drivers using the intersection frequently. Driver familiarity with the system should therefore be assumed when trying to determine where he will react to a speed signal. Probably he will react to an unchanging speed instruction some distance before reaching the signal itself, but will react to any change in the speed signal whenever that change occurs while the signal is visible to him.

Visibility thus also is a factor. In this case, good visibility may be a disadvantage, because it spreads out the length over which drivers will see and react to the speed message given, especially when it is changing.

Further clarification of this point (as well as of those following) will have to be found by experimentation in the field.

Actual Speed Change Pattern

Speed changes are primarily reductions from free flow speed, requiring some deceleration to the suggested approach speed. Although the computations in this paper assume instantaneous speed change, the actual deceleration rates will likely be those of coasting at about 1 mph per sec. For small speed changes of 10 mph or less the effect of the gradual speed change is negligible, especially because most drivers will probably begin the speed change ahead of the signal. But for larger speed changes the effect should be considered for each application. It will require larger speed differences because the gradual change delays the attainment of the new speed.

Speedometer Accuracy

Most automobile speedometers give speed indications 5 to 10 percent higher than the actual speed. This factor should be considered in designing a traffic funnel application. One way is to set the speed indications at the entrances to the traffic funnels 5 to 10 percent higher than actually desired. Particularly the last vehicle approaching at free flow speed would (if its speedometer indicated too high a speed) travel too slow to reach the intersection during green time. For these last vehicles an overcorrection might even be necessary.

It will be necessary to check field applications for possible variations from the theoretical computations and to make any adjustments that might become necessary. Motorists too will adjust their driving habits to fit properly into the traffic funnel, although this correction will never be as efficient as the appropriate correction in the system design.

GENERAL APPLICATIONS

There are essentially two applications of the principle of controlling the speed of approach to intersection traffic control: (a) the complete traffic funnel, and (b) the partial traffic funnel.

The complete traffic funnel can be used on isolated intersections where the rather long approach distances can be accommodated. It can also be used on entrances into arterial roads with progressive signal systems.

The partial traffic funnel is used in the form of a "traffic pacer" to give speed recommendations on comparatively short roadway sections between signalized intersections. It can be used to guide the motorist through any progressive signal system, but is especially necessary in systems in which the speed of progression changes. It can also be used to redistribute the traffic flow bands between signal systems of varying cycle length.

APPLICATION OF APPROACH SPEED SIGN

An extremely inexpensive application of the principle of controlling the speed of approach by signs can be used on many intersections where the conditions are favorable.

Description of the Device

Figure 4 shows that the recommended approach speed is different for different phases of the signal indication and any given instruction for approach speed must be matched to the duration of the phase on the signal ahead. Furthermore, it is necessary that the approaching driver sees the signal and its light indication from the location of the

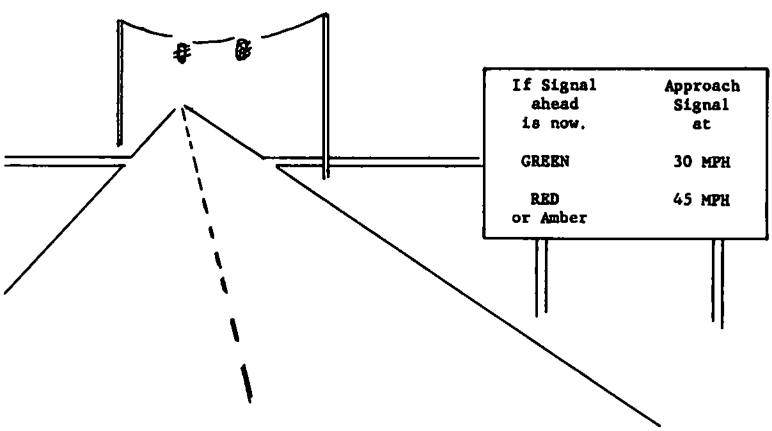


Figure 4. Principle of approach speed sign.

approach speed sign. The device will work on fixed-time signals, with the green phase either longer or not much shorter than the red phase. It is, of course, not necessary to apply approach speed control to all approaches of an intersection.

Evaluation of the Control of Speed of Approach with Signs

The primary advantage of controlling speed of approach with signs only is the very low cost. Controlling approach speed by speed signals costs as much as or more than the original signal installation. In these circumstances, exploring the possibility of using a sign to control speed of approach is certainly justified.

Because controlling the speed of approach never increases the free approach speed nor overrides the signal indication, the use of an approach speed sign should not create a worse situation than exists at the signal without such a sign. Many drivers already attempt to adjust their speed when approaching a signal, but are often thwarted by lack of clues. A sign indicating speed of approach could be a boon. Any such operational advantage will justify the small expenditure for a sign advising speed of approach.

If some drivers do not comprehend the message at first passage, no harm is done. But those who pass through that intersection repeatedly will quickly adapt to the system and even make their own adjustments for speedometer inaccuracy or other individual peculiarities.

Approach speed control signs can be used with considerable savings at those approaches to an intersection, which have the required visibility. At other approaches, speed signal systems can be used for controlling speed of approach. If visibility of the signal indication is not always assured, the period of effectiveness of the sign will be reduced, but no harm will be done, and the gains will still be high during the time when the sign is useful.

Computation for Approach Speed Signs

The basic relationships discussed in connection with Figure 2 hold here with the following modifications. Because the timing of the approach speed indication must be identical with the signal cycle timing, the approach time t_1 becomes equal to the duration of the green phase t_g (or the entire cycle duration t_c). The given values in this case are the times of the signal phases and the free approach speed. The needed values are s (the approach distance), indicating how far in advance of the intersection the approach speed sign must be located, and V_2 (the slow approach speed).

Similar to the previous computations,

$$V_1 = \frac{s}{1.47\, t_g} \qquad V_2 = \frac{s}{1.47\,(t_g + t_r)} = \frac{s}{1.47\, t_c} \tag{9}$$

giving

$$V_2 = \frac{t_g}{t_c}\, V_1 \sim \tfrac{1}{2}\, V_1 \tag{10}$$

and

$$s = 1.47\, V_1\, t_g \tag{11}$$

A time-gap triangle for this type of control of the speed of approach is shown in Figure 5. The slow approach speed is related to the free approach speed as the green phase is related to the cycle length. This ratio would in the average be about one-half, thus requiring a speed reduction for the slow approach speed to one-half the free approach speed. This is a rather drastic speed reduction. Longer approach distances, with an approach time equal to an entire cycle length (as shown in Fig. 6), will permit less marked reductions. Eqs. 10 and 11 will then be written:

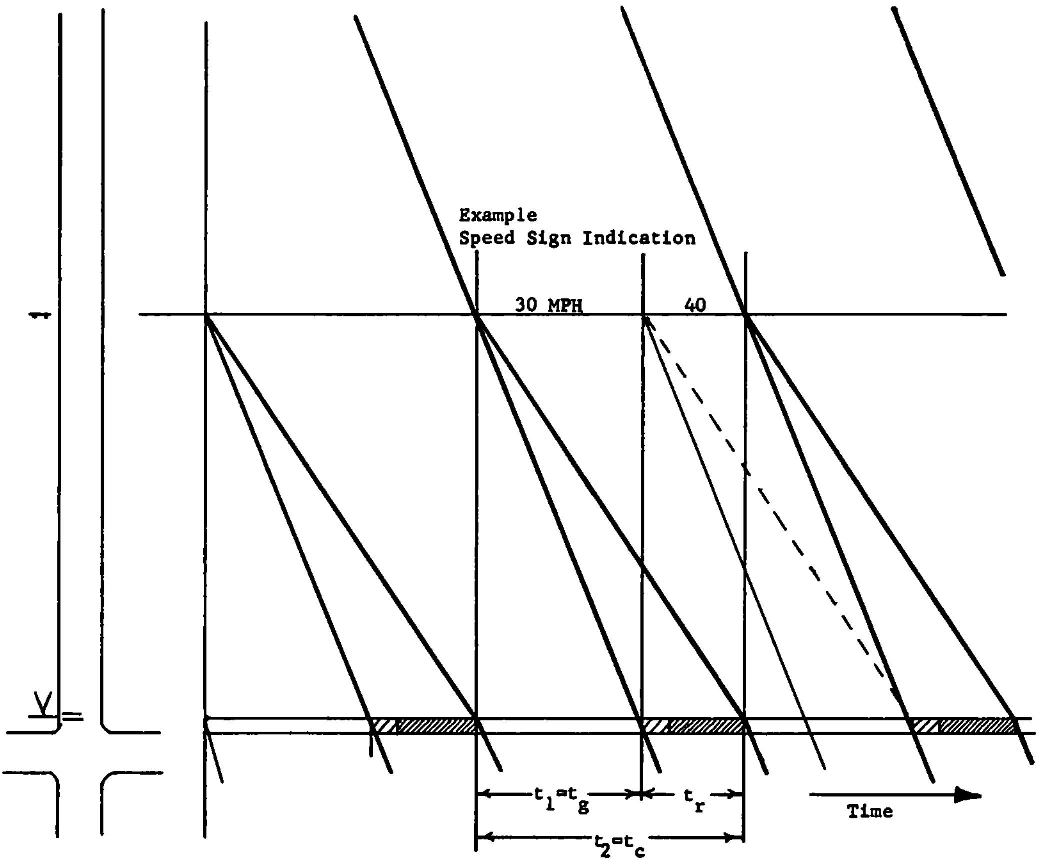
$$V_1 = \frac{s}{1.47\,t_c} \qquad V_2 = \frac{s}{1.47\,(t_c + t_r)} \tag{12}$$

and

$$V_2 = \frac{t_c}{t_c + t_r} \quad V_1 \sim \tfrac{2}{3} V_1 \tag{13}$$

$$s = 1.47\,V_1\,t_c \tag{14}$$

Although the approach distance now is about twice as long as in the previous case, in some cases a second sign controlling the speed of approach can be installed closer

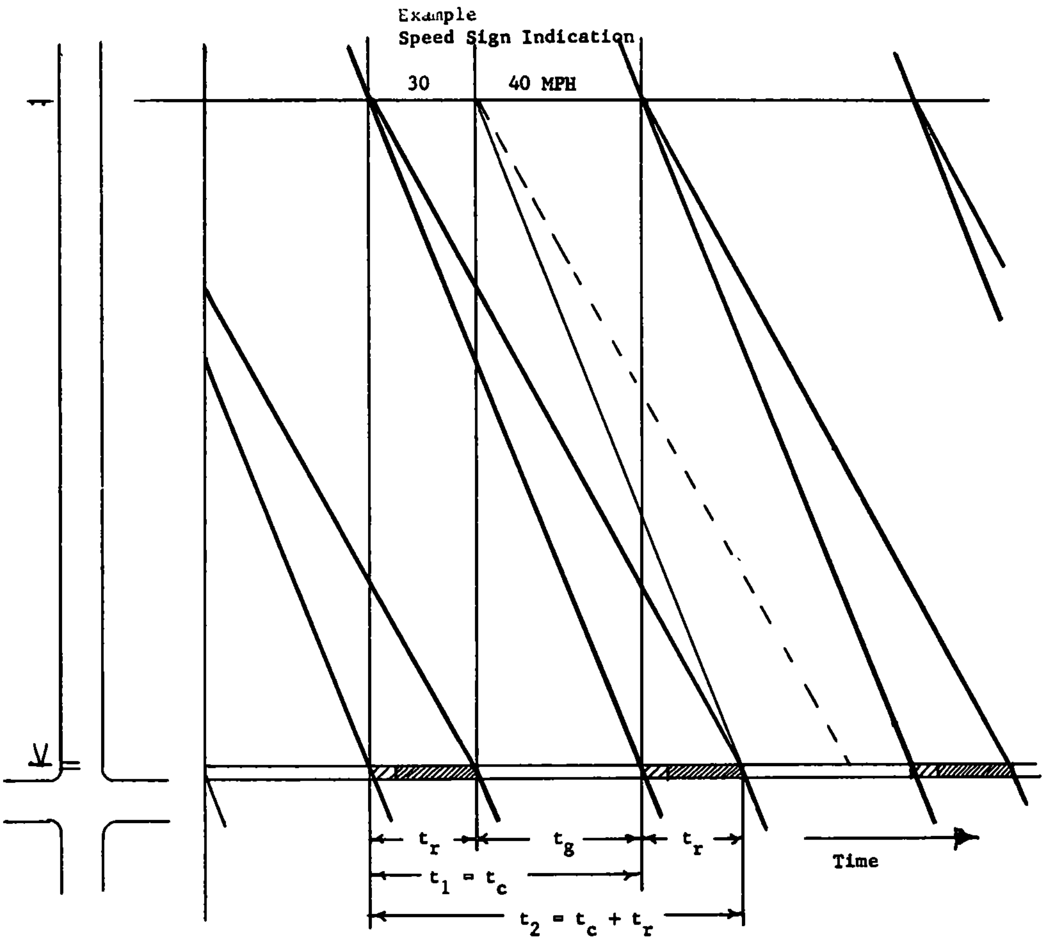


$t_1 = t_g$ = Green Signal Phase

$t_2 = t_c$ = Signal Cycle Time

$V_2 = \frac{t_g}{t_c} V_1$

Figure 5. Approach speed sign with one-phase advance.



$t_1 = t_c$ = Signal Cycle Time

$t_2 = t_c + t_r$

$$V_2 = \frac{t_c}{t_c + t_r} V_1$$

Figure 6. Approach speed sign with one-cycle advance.

to the intersection, superimposing a funnel based on the one-phase advance. Superposition of those two funnels might improve approach speed control and assure better performance on these long approaches.

For instance, a free approach speed of 50 mph and a green phase of 30 sec in a cycle of 60 sec would require that the approach distance in the first case be 2,200 ft, with a required speed reduction for the slow approach speed to $\frac{1}{2}$ of the free approach speed. In the second case, the approach distance would be 4,400 ft and the slow approach speed equal to $\frac{2}{3}$ of the free approach speed. Of course, this example is given for rather high-speed intersections, where good approach visibility is often available.

Approach Speed Sign Application

The three causes for discrepancy between theoretical computations and the facts in actual applications of signals controlling speed of approach hold equally for the approach speed sign. The rather large speed reduction required with the use of a sign increases the difference between an assumed instantaneous speed change and the actual gradual deceleration on the highway, thus increasing this source of inaccuracy.

CONCLUSION

For the motorist, great potential benefits can be gained by controlling the speed of approach at intersections. The principles and theories outlined here will help in determining the best application of this control method for each practical case.

The low cost of signs for controlling speed of approach should encourage experimentation with this method.

Methods of Traffic Measurement–Determination of Number and Weight of Vehicles

STIG EDHOLM, Chief, Traffic Research Department, National Swedish Road Research Institute, Stockholm

The National Swedish Road Research Institute has designed and constructed a small transportable scale for measuring the axle loads of vehicles in motion. This scale consists of a platform installed in the road pavement and an instrument case placed on the side of the road. The scale platform rests on three load-sensitive devices operating on the strain gauge principle. Only the wheel load at one end of an axle is recorded. The dimensions of the platform are small: length, 1 ft 8 in.; width, 4 ft 7 in.; depth 4⅜ in. This is required for two reasons: the platform should be easy to transport, and the cost of the foundation in the road pavement should be low. The measurements are automatically recorded on a strip chart when vehicles pass the platform. The scale also serves as a traffic counter inasmuch as the chart data are evaluated so that the recorded vehicles can be classified into various groups according to magnitude, number, and spacing of recorded axle loads.

In Sweden, since January 1961, the National Swedish Road Board has been conducting regular measurements at about 200 weighing sites, which are distributed over the whole country. These measurements are made by 5 patrols. The results of the measurements indicate that certain simple relations exist between the number of vehicles passing a road section per unit time and the total vehicle weight or the total pay load of these vehicles in each group of vehicles. Extensive investigations have been made to determine these relations.

A small-sized traffic counter is being tested at the present time. This counter not only counts the number of vehicles passing the road section under observation but also records the group of vehicles to which each individual vehicle belongs. Patents covering the principles of this traffic counter have been applied for.

•FOR MANY YEARS the National Swedish Road Board has been conducting both mechanical and manual traffic counts. The mechanical counts take place at a very large number of observation points. The results of these counts are obtained in terms of the total number of axles that have passed the observation point during the counting period in both directions of travel taken together. To determine the distribution of the vehicles among various vehicle groups, the mechanical counts are supplemented with manual counts. The results of the mechanical traffic counts are represented in flow maps, which show the average daily traffic for the whole year and the average daily traffic for the summer on most roads in Sweden. Moreover, some other, less extensive traffic investigations (e g., destination studies) are made in this connection.

The traffic data collected in this way serve as a basis for priority estimates, planning and design of new roads, allocation of maintenance grants, forecasting, surveys of traffic development, etc.

The rapid growth of road traffic during the past few years has caused an increase in the costs of maintenance, improvement, and extension of the Swedish road system. It is therefore necessary that these estimates, etc., should be made with a greater precision than that which is possible at the present time. However, this requires more detailed information on traffic, particularly commercial vehicle traffic. For instance, data on the total weight of the commercial vehicles that travel along various roads on an average per day and data on the composition of the traffic on the roads studied in this connection would constitute a valuable supplement to the results of the other traffic measurements.

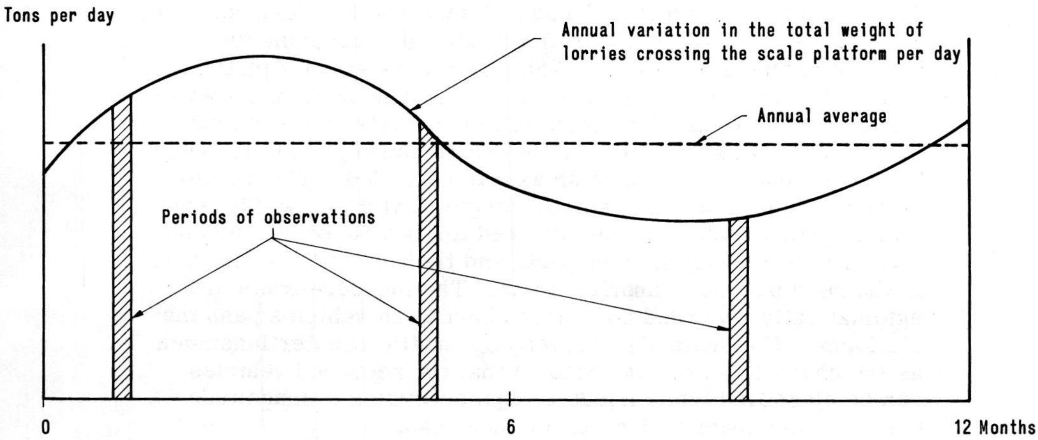


Figure 1. Random sampling procedure in axle load measurements.

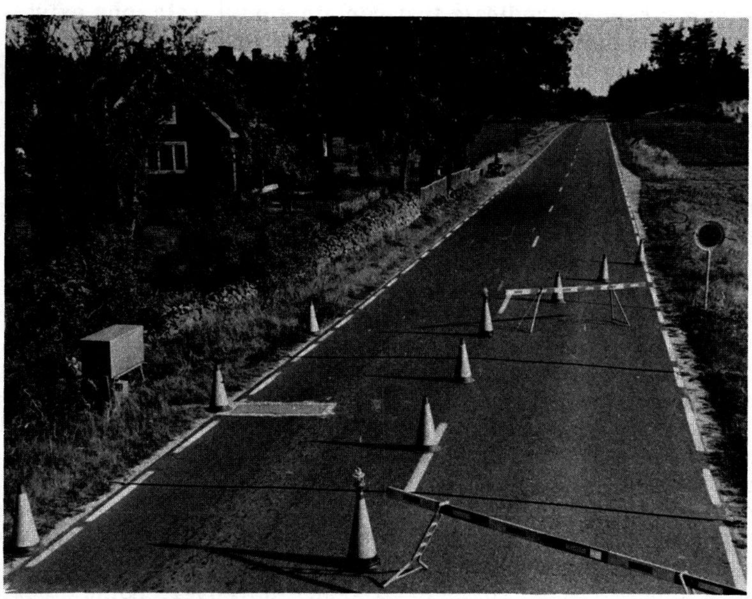


Figure 2. Weighing site. Scale platform visible on left side of road.

For this reason, the National Swedish Road Board has requested the National Swedish Road Research Institute to design and to construct appropriate equipment for measuring the weight of moving vehicles at a great number of observation points, approximately 200. Such a weighing equipment should entail a low first cost and a low operating cost. Furthermore, it should be easily transportable from one site to another, fully automatic in operation, and equally well suited for summer and winter use.

Measurements made to determine the total weight of the commerical vehicles that pass an observation point on an average day during a year, just as the traffic counts made for the purpose of determining the average daily traffic for the whole year, must be carried out on a random sample basis; e.g., by using three periods of observation per year (see Fig. 1). The error involved in such measurements is made up of the following two component errors:

1. The random sample error; i.e., the error due to the fact that the calculation is based on values obtained during a small number of short observation periods, and not during the whole year.
2. The error in measurements that is involved in the determination of the weight of vehicles.

The number of observation periods per year shall be adapted to the accuracy required. The error in measurements made for determining the weight of vehicles may be assumed to be small in comparison with the random sample error allowed in these studies.

AXLE LOAD SCALE

The considerations just outlined were taken by the National Swedish Road Research Institute as a point of departure for the design and construction of a scale equipment that should measure the axle loads of moving vehicles without necessitating their stopping. This scale equipment consists of a load-sensitive platform installed in the road pavement. This platform is connected by a cable to an instrument equipment, which is enclosed in a sheet aluminium case (see Figs. 2 and 3). When a vehicle moves across the platform, the load applied by each axle to the platform is recorded. The total weight of the vehicle is obtained by adding together the loads due to all axles of the vehicle. The scale is fully automatic in operation, and needs to be looked over only a few times per day.

Weighing Site

The scale platform extends across about one-half a traffic lane (see Fig. 2). Only the wheel loads at one end of an axle are measured, and the axle loads are obtained by multiplying the observed wheel loads by a factor equal to 2 for roads without any lateral slope. For roads with a lateral slope, the value of this factor is less than 2. If the speed at these weighing sites is restricted to 20 km per hr (12.5 mph), then the weighing can be carried out with sufficiently high accuracy even when the road pavement before and behind the platform is not particularly even. Accordingly, a scale platform can be installed in the road pavement without necessitating in general any adjustment of the road surface. On gravel roads, however, the carriageway should be covered with a suitable surfacing about 25 m (80 ft) before and behind the platform to prevent pitting. When the platforms are removed from the foundations after completion of measurements, they are replaced by wooden fill-in slabs.

On roads handling a large flow of traffic, a platform is installed in each traffic lane, and the traffic at the weighing site is canalized in an appropriate manner. If the traffic flow is small, then the platform is located in one lane only, while the other lane is shut off, and meeting restrictions are established at the weighing site (see Fig. 2). The direction of travel of each vehicle is recorded at the same time as the axle load.

Foundation

The scale platform is screwed to a foundation embedded in the road pavement. The top surface of the platform is set level with the road surface. The dimensions of the platform are small: length, 0.5 m (1 ft 8 in.); width, 1.4 m (4 ft 7 in.); and depth, 0.11 m (4⅜ in.). This is required for two reasons: (a) the platform should be readily transportable, and (b) the construction cost of the foundation in the road pavement should be low.

The foundations are constructed in pits excavated in the road pavement. Each pit is about 30 cm (1 ft) longer, wider, and deeper than the scale platform. The foundations are made of reinforced concrete. A steel frame is embedded in each pit. This

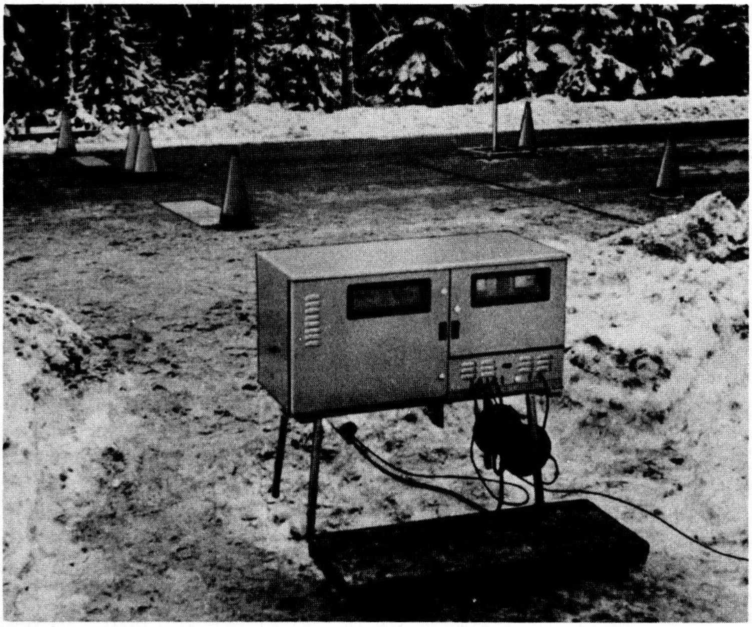


Figure 3. Instrument case.

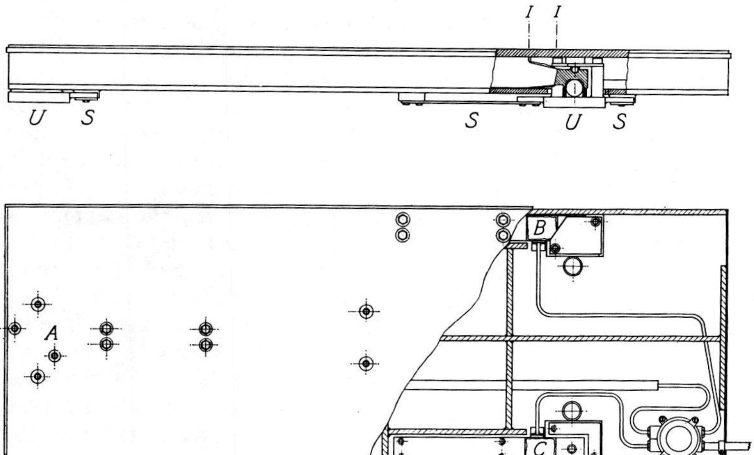


Figure 4. Scale platform.

frame constitutes the walls of a rectangular trough, 12 cm ($4\frac{3}{4}$ in.) in depth, in which the platform is placed and fastened.

The bottom of the foundation is provided with a large-sized drain pipe. The platform is attached to the foundation by bolts screwed into threaded holes in the steel frame. The construction of a foundation takes only a few hours.

The clearance between the platform and the walls of the foundation is sealed with a rubber gasket, so as to prevent the entry of water, snow, sand, etc.

Scale Platform

The platform is a welded steel plate structure connected without any play to two seating strips U (see Fig. 4) which are screwed to the foundation when the platform is installed. Vertical forces are transmitted to the seating strips by three load cells A, B, and C, and horizontal forces are transmitted by three thin supporting springs S.

As these supporting springs are relatively soft, the seating strips U, which support the load cells by means of steel balls, can turn so that they abut the supporting surfaces in the foundation. Furthermore, the platform rests at three points only. Therefore, the geometrical accuracy in the construction of the foundations can be comparatively low without jeopardizing the possibilities of stable attachment of the platform to the foundation. Consequently, the costs of construction of the foundation can be kept low, the installation of the platform is easy to carry out, and no subsequent adjustment is needed.

The load cells operate on the wire resistance strain gauge principle. Each load cell consists of a steel bar, which is screwed into the platform at one end, whereas the other end is clamped by means of a flat spring between two steel balls in the seating strip. Disturbing bending moments cannot be transmitted through these balls to the load cell. When the scale platform is subjected to a load, the load cells are submitted to a bending stress. In the free portion I - I, this stress is proportional to the load. The magnitude of the bending stress is measured by means of wire resistance strain gauges.

Figure 5 shows the wire resistance strain gauge used in this scale. The strain-sensitive wire, about 0.025 mm (1/1,000 in.) in diameter, in the form of a zig-zag coil is cemented on a paper, bakelite, or plastic support. The strain gauge is cemented on the surface at the point of measurement.

Four wire strain gauges A, B, C and D are attached to each load cell (see Fig. 6). They are connected together to form a measuring bridge network (see Fig. 7). An AC voltage is applied to this network at the dividing points 2 and 4. When the load cell is submitted to a load, this causes an increase in the resistance of the strain gauges C and D (which are subjected to tension) and a decrease in the resistance of the strain gauges A and B (which are subjected to compression). Accordingly, an out-of-balance voltage is produced across the dividing points 1 and 3 of the bridge network, and this voltage is proportional to the load acting on the load cells.

Because the platform rests on the three load cells, the load on the scale is equal to the sum of the loads on these load cells. If the measuring networks of the three load cells are connected in parallel, then a resultant out-of-balance voltage is obtained that is proportional to the total load on the platform.

Instrument Equipment

The out-of-balance voltage, which is very low, is amplified in a carrier frequency amplifier. This amplifier is also used as an AC voltage source for the measuring bridge networks.

The output current of the carrier frequency amplifier is fed to a galvanometer loop in a direct-recording instrument, which is known as ink jet recorder. The galvanometer loop is provided with a nozzle, which projects a thin ink jet with a high velocity on strip chart paper, about 12 cm ($4\frac{3}{4}$ in.) in width, which is fed at a constant speed. The ink jet traces a fine line, whose position on the strip chart is determined by the direction of the ink jet; i.e., by the angle of deflection of the galvanometer.

The strip chart paper need not be specially treated, and is therefore cheap. Folded strip chart paper is used at the present time, and a packet of chart paper is sufficient for recording some 6,000 vehicles.

The strip chart paper in the recorder is started when a vehicle passes over a rubber tube that is stretched across the road about 3.5 m (11 ft 6 in.) in front of the platform and actuates a diaphragm switch. A time lag attachment, which is controlled by the pulses emitted from the diaphragm switch, keeps the strip chart paper moving until all axles of the vehicle have passed across the platform and their loads have been recorded.

A block diagram of the equipment is shown in Figure 8. Care was taken to insure that the sensitivity of the scale be constant during a period of observation; e.g., a week. This problem was of paramount importance in the experimental stage. It was solved by taking the following measures:

1. The load cells and the cable connections were provided with highly reliable electric insulation to prevent the entry of water, which can cause insulation faults.
2. The temperature in the interior of the instrument case is maintained constant by means of a thermostat-controlled electric hot-and-cold unit.
3. The supply voltage is kept constant at 220 V by means of a supply voltage stabilizer.

The insulation resistances of the load cells, wire strain gauges, and conductors as well as the sensitivity of the carrier frequency amplifier and the recorder are automatically controlled every hour. For this purpose, a resistance is connected in parallel with the wire strain gauges A in the parallel-connected measuring bridge networks (see Fig. 7). This resistance has been adjusted so that the out-of-balance voltage that it produces in these bridge networks is equal to that caused by a load of 5 metric tons on the platform. Consequently, if the equipment is in perfect working order, then the recorder records a check pulse corresponding to 5 metric tons during, say, 3 sec every hour. At the same time, the strip chart is stamped automatically with the time

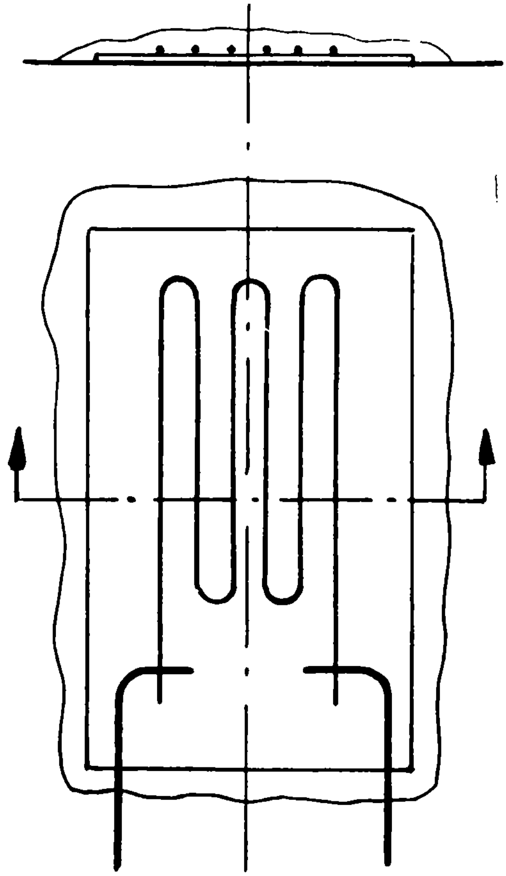


Figure 5. Wire resistance strain gauge.

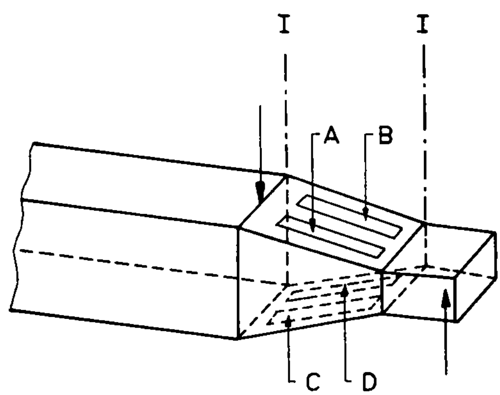


Figure 6. Location of wire resistance strain gauges on load cell.

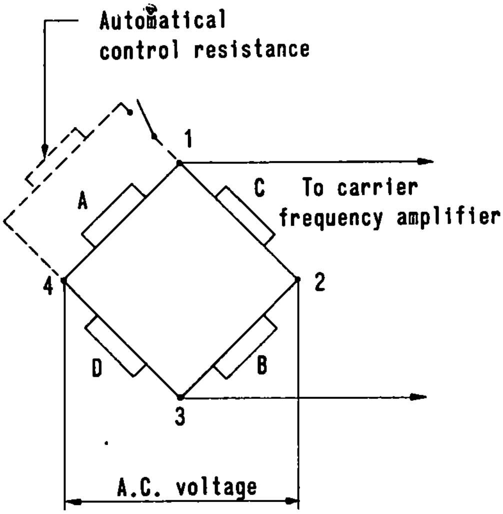


Figure 7. Measuring bridge network.

(in hours and minutes) of this check recording. The time can also be stamped manually on the strip chart by pushing a button in the instrument case. This manual time stamping is used as a check when the patrolmen inspect the equipment, calibrate the scale, etc.

For calibration, the platform is loaded by the aid of a hydraulic jack, and the magnitude of the load is measured with a mechanical load gauge. The scale is usually calibrated twice every week. The whole calibration procedure takes about 10 min.

MEASUREMENTS

Variation in Load Across Scale Platform

The scale should be capable of reproducing faithfully the variation in load which takes place when a vehicle crosses the platform. A schematic diagram representing the variation in load during the passage of a wheel across the platform is shown in Figure 9. When the center of the wheel moves from A to B, the wheel rolls from the road pavement on to the platform. Between B and C, the whole surface of contact of the wheel rests on the platform. When the center of the wheel moves from C to D, the wheel leaves the platform and moves on to the road pavement. The height H in this figure is a measure of the wheel load.

At a speed of 20 km per hr (12.5 mph), the time during which the whole wheel load (e.g., 4 metric tons) is acting on the platform is only about 0.05 sec. The scale must

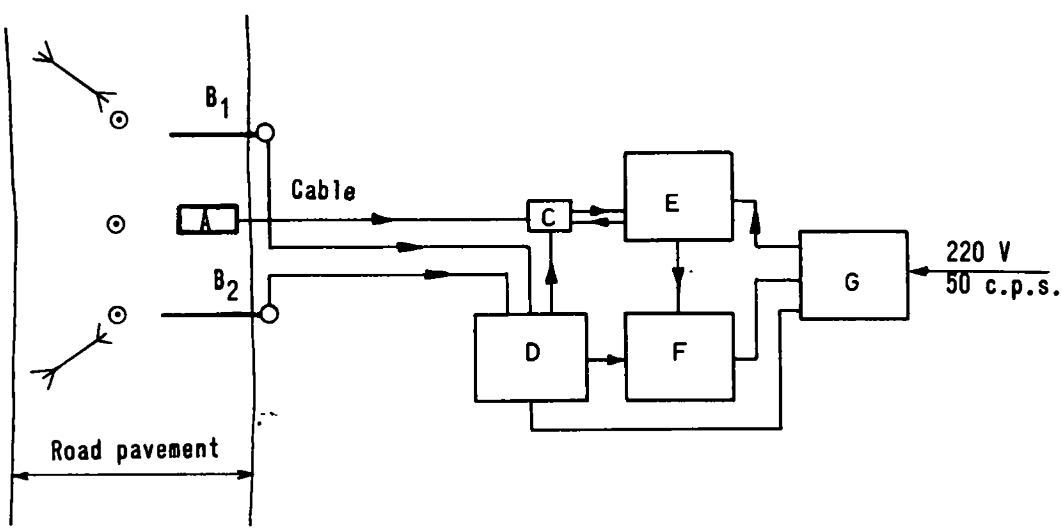


Figure 8. Block diagram. A = scale platform; B = rubber tube; C = connection box; D = automatic control unit; E = carrier frequency amplifier; F = recording instrument; G = supply voltage stabilizer.

therefore be capable of reproducing rapid variations in load. This was achieved by designing the scale to obtain suitable characteristics, such as high natural frequency, a low weight of the platform, and a high spring constant of the load cells.

The recorder must also be capable of reproducing these rapid variations in load without involving any appreciable errors.

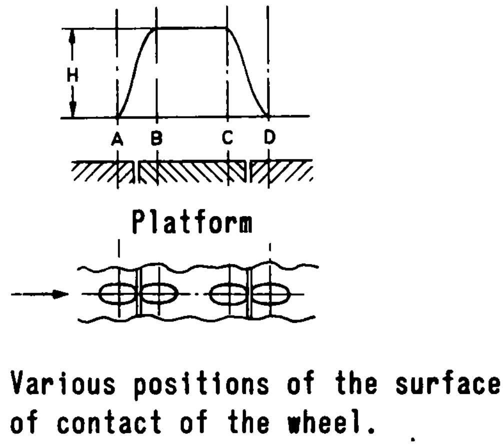


Figure 9. Variation in load across platform.

Dynamic Increment

The axle load acting on the road pavement (or on the platform of the scale) when the vehicle is in motion differs from that caused by a vehicle at rest. This difference, which can be positive or negative, is known as the dynamic increment. It is usually due to irregularities of the road surface and to deviations from true roundness of the wheels, which give rise to vibrations of the wheels and the body of the vehicle. Moreover, acceleration and retardation produce differences in load which are also regarded as dynamic increments.

Accuracy in Measurements

The purpose of the measurements just described was primarily to determine the sum of the axle loads of the vehicles passing a weighing site during a sufficiently long period of time. The scale in question is well adapted for this particular purpose because the difference between the positive and negative dynamic increments is relatively slight. However, the dynamic increment in an individual observation can be comparatively large. Extensive studies dealing with the magnitudes of the dynamic increments in individual observations as well as in sums of observations are being planned to be carried out in 1962. A new method for these extremely intricate studies is being devised.

To illustrate the studies of the magnitude of the dynamic increment made up to the present time, the results of a small investigation are reproduced. This investigation was carried out on two scales that were installed on the same road at a distance of about 25 m (80 ft) from each other. The road pavement at the weighing site did not comply with the necessary requirements in respect of evenness. This investigation comprised measurements on 35 axles of lorries in one direction of travel and 18 axles in the other. The axle loads were measured, first, on each vehicle at rest, and then, on the same vehicle while it was crossing the platforms at a speed of about 25 km per hr (12.5 mph). For the vehicles at rest, the recorded sum of the axle loads was found to be 318.5 metric tons on the scale 1 and 316.5 metric tons on the scale 2.

In the measurements made on the vehicles moving across the platform, the respective sums were 326.0 and 326.1 metric tons. In other words, the respective deviations from the results of measurements on the vehicles at rest were 2.4 and 3.0 percent. The sum of the axle loads of the vehicles at rest obtained by means of the scale 1 was 0.6 percent greater than that observed by the aid of the scale 2. This can be due to errors in calibration or in readings. It was not possible to carry out a separate investigation in each direction of travel because the number of vehicles was too small.

A more detailed report on the accuracy in measurements will be published later.

Strip Chart and Its Evaluation

A specimen of a strip chart recorded at a weighing site where the platform was installed in one traffic lane only is shown in Figure 10. The upper curve represents the magnitude of the axle load, and the lower curve indicates the direction of travel. Vehicles moving in one direction are marked by positive pulses when the vehicle crosses the rubber tube in front of the platform. In that case, the rubber tube behind the platform is blocked. Vehicles traveling in the opposite direction are marked in an analogous manner by negative pulses.

If the weighing site is equipped with a platform in each traffic lane, then the upper curve represents the axle loads of the vehicles traveling in one direction, and the lower curve shows the axle loads of the vehicles moving in the opposite direction. In such cases, the impulses emitted from the rubber tube in front of each platform are recorded as a third, intermediate curve on the strip chart. The rubber tubes are situated at a distance of 3.5 m (11 ft 6 in.) from the platform (see Fig. 2). In evaluating the strip charts, it is therefore possible to find out whether the wheelbase of a vehicle is longer or shorter than 3.5 m (11 ft 6 in.) (see Fig. 10).

The data are transferred manually from the strip chart to special printed punched cards (mark-sensing cards) by marking them with India ink (see Fig. 11). The information conveyed by each ink mark is then mechanically punched on the card. Each card comprises three columns for each axle; viz., two columns for the axle load and one column for a mark indicating whether the axle in question is a single axle or a front or rear axle in a bogie. Each set of columns for each axle on the card has a number (1, 2, etc.). The data relating to the first axle of the vehicle, reckoned from the front, are entered in the set of columns No. 1, the data referring to the second axle are marked in the set of columns No. 2, and so forth.

A special column is used to indicate whether the wheelbase of the motor vehicle is longer or shorter than the distance from the rubber tube to the platform; i.e., 3.5 m (11 ft 6 in.). This indication is employed for classifying the vehicles into groups. In evaluating the magnitudes of the axle loads, use has so far been made of a transparent rule graduated in metric half-tons. For taking readings, this rule is laid on the strip

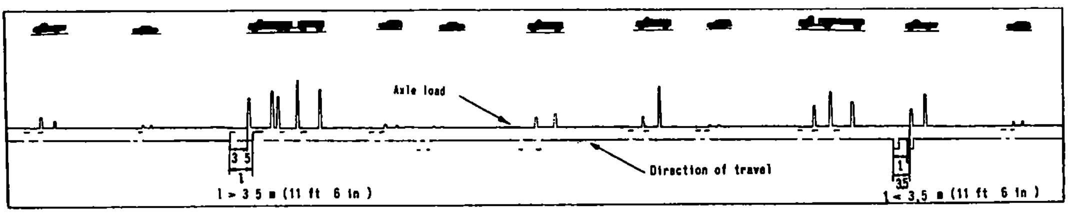
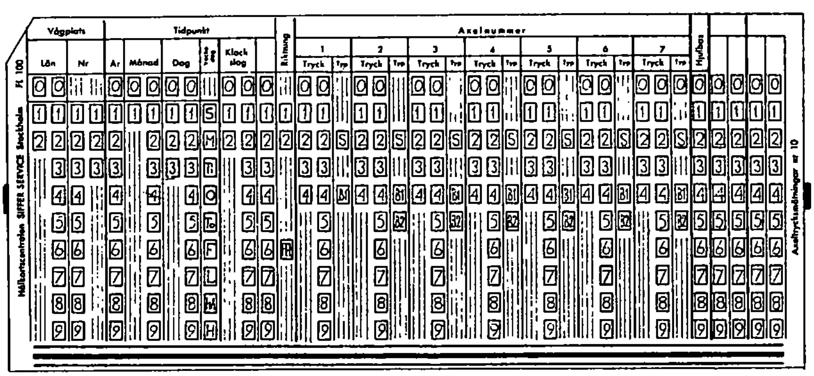


Figure 10. Specimen of strip chart.



Explanatory notes	
Vågplats	Weighing site
Tidpunkt	Time
Axelnummer	Axle No
Län	County
Nr	No.
År	Year
Månad	Month
Dag	Day
Veckodag	Day of the week
Klockslag	Hour
Riktning	Direction
Tryck	Axle load
Typ	Type of axle
Hjulbas	Wheelbase

Figure 11. Punched card (mark sensing).

chart. The number of private cars (i.e., vehicles weighing less than 2.5 metric tons) is counted separately.

The punched cards are fed to a data-processing machine, which classifies the vehicles into groups that are closely in accordance with the transport functions of the various types of vehicles. Figure 12 shows the types of vehicles that belong to the different groups of vehicles. This group classification is employed in Sweden at the present time in connection with the axle load measurements.

Owing to the use of this method of evaluation, the scale equipment just described can also be used as a vehicle-differentiating traffic counter.

This method of evaluation is relatively labor-consuming, but it enables the treatment of the data obtained from the measurements to be advanced very far. In this way, administrators, researchers, etc., can be furnished with particularized information on the traffic in a traffic flow.

The possibility of constructing a machine for automatic transfer of the requisite data from the strip chart to punched cards or tape is being studied at the present time.

The punched cards are handled in conformity with various programs. For example, the following characteristics of the vehicles passing the scale platform per unit time can be calculated:

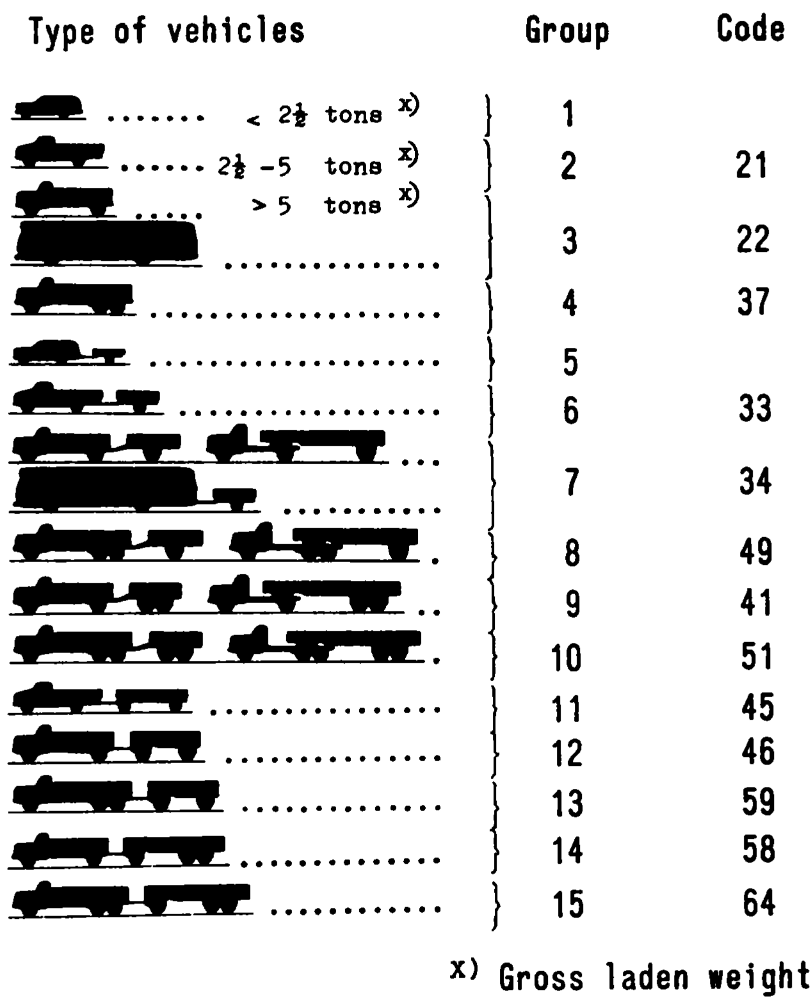


Figure 12. Types of vehicles in different groups.

1. Total number of vehicles.
2. Number of vehicles in each group of vehicles.
3. Total vehicle weight of all lorries.
4. Total vehicle weight of lorries in each group of vehicles.
5. Total vehicle weight of various units in road trains (e.g., the tractor or the trailers) in each group of vehicles.
6. Distributions of observed vehicle weights and axle loads or bogie loads.
7. Estimated total pay load of the vehicles defined under 3, 4, and 5 (this requires the reading-in of certain constants in programing the data-processing machine).

Measurements Made During Experimental Period

The first measurements with an experimental scale were started in May 1959. A second scale was constructed in the same month, and measurements were made at three weighing sites in June. These measurements, which were carried out in collaboration with the National Swedish Road Board, showed that it would be possible to use this scale for ordinary traffic measurements. The Board therefore gave the Institute an order for three complete weighing equipments to be used for more extensive tests. These equipments were ready for use in the autumn of 1959.

RESULTS

The results of some investigations are briefly summarized in what follows. These investigations are based on the data obtained from the axle load measurements made when the scale equipment was tested in 1959 and 1960 at 29 weighing sites in Central and Northern Sweden, sometimes under winter conditions. The measurements at each weighing site were as a rule performed during 5 days. These data comprise axle load recordings relating to 16,500 lorries in all.

Figure 13 shows the mean axle loads in different groups of vehicles. This figure shows, among other things, that the axle loads generally increase with the size of the vehicle (the number of axles).

Table 1 gives the make-up of the traffic and the total weight of lorries (divided into two groups; viz., light lorries, with two or three axles, and heavy lorries, with more than three axles) during a measuring period of three days and nights (weekdays). These data were obtained from measurements made at the following weighing sites:

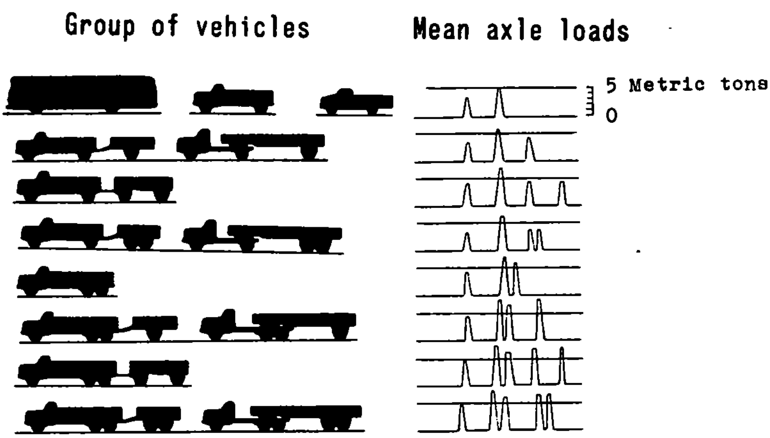


Figure 13. Mean axle loads in different groups of vehicles; 16,500 lorries, 29 weighing sites in central and northern Sweden, 1959 - 1960.

TABLE 1

RESULTS OF AXLE LOAD MEASUREMENTS[1]

Road	Measurement Date	No. of Hours	No. of Private Cars	2- or 3-Axle No	2- or 3-Axle %	2- or 3-Axle Weight (met. T)	Over 3-Axle No.	Over 3-Axle %	Over 3-Axle Weight (met T)	All No.	All %	All Weight (met T)
Nat. Main 12[2]	Jan 1960	59	2,093	612	54	4,943	170	46	4,163	782	100	9,106
County 233[3]	Jan -Feb. 1960	60	1,069	406	78	3,930	53	22	1,129	459	100	5,059
County 735[4]	June 1959	59	897	232	51	2,228	93	49	2,210	325	100	4,498
	Jan. 1960	62	634	209	53	1,837	68	47	1,615	277	100	3,452
County 356[5]	Sept 1959	63	499	179	91	1,529	7	9	143	186	100	1,672
	March 1960	63	566	164	40	1,674	84	60	2,466	248	100	4,140

[1] Each measurement carried out during three successive days and nights (weekdays).

[2] In Grådo, Kopparberg Co., carrying National Main Road traffic.

[3] Through road in Balhyttan, Varmland Co., carrying certain amount of timber traffic.

[4] In Intrånget, Kopperberg Co., carrying mining transport predominantly.

[5] Through road in Korstrask Co , carrying timber transport predominantly.

1. Grådö, National Main Road 12, County of Kopparberg. National Main Road traffic.
2. Bolhyttan, County Road 223 (through road), County of Värmland. A certain amount of timber transport.
3. Intrånget, County Road 735, County of Kopparberg. Mining transport predominant.
4. Korsträsk, County Road 356 (through road), County of Norrbotten. Timber transport predominant during the winter.

For the first two sites, the table gives only the results of measurements carried out during the winter. A comparison of the results obtained at these two sites shows that the heavy lorries, with more than three axles, were more predominant on the National Main Road than on the through road. At Intrånget, where the mining transport predominates, the weight percentages in the two groups of lorries are approximately equal in June and in January, whereas at Korsträsk, where the timber transport predominates, the weight percentage of lorries with more than three axles in the winter is seven times as great as in the summer.

Figure 14 shows that the mean percentages of lorries were as follows: two-axle lorries, about 60 percent; three-axle lorries, about 20 percent; four-axle lorries, about 13 percent; and five-axle lorries, about 7 percent of the total number of lorries. Furthermore, this diagram represents the mean vehicle weights in the various groups of vehicles. These weights were estimated from the total recorded data. The mean unladen weights given in Figure 14 are based on a survey of the register of motor vehicles in the County of Kopparberg. Furthermore, this figure also indicates the ratio of the mean pay load to the mean vehicle weight in each group of vehicles.

The number of two-axle lorries, expressed in percent of the total number of lorries at the various sites, varied from 28 to 93 percent. The relation between the number and the weight of two-axle lorries, expressed in percent of the total number and the total weight, respectively, of lorries, is shown in Figure 15. The curves in this graph are based on the mean weights tabulated on the right. This relation has been confirmed by the values observed at the various weighing sites. For instance, as is seen from the graph, if 60 percent of all lorries at a weighing site are two-axle lorries, then they correspond to about 40 percent of the total vehicle weight and to about 30 percent of the total pay load of the lorries passing the weighing site in question. This result shows that an appropriate classification of vehicles into groups is of fundamental importance in determining those characteristics of traffic that are significant from a transport point of view.

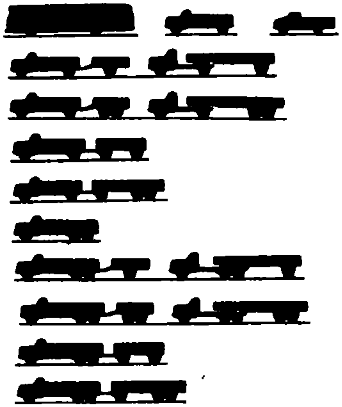
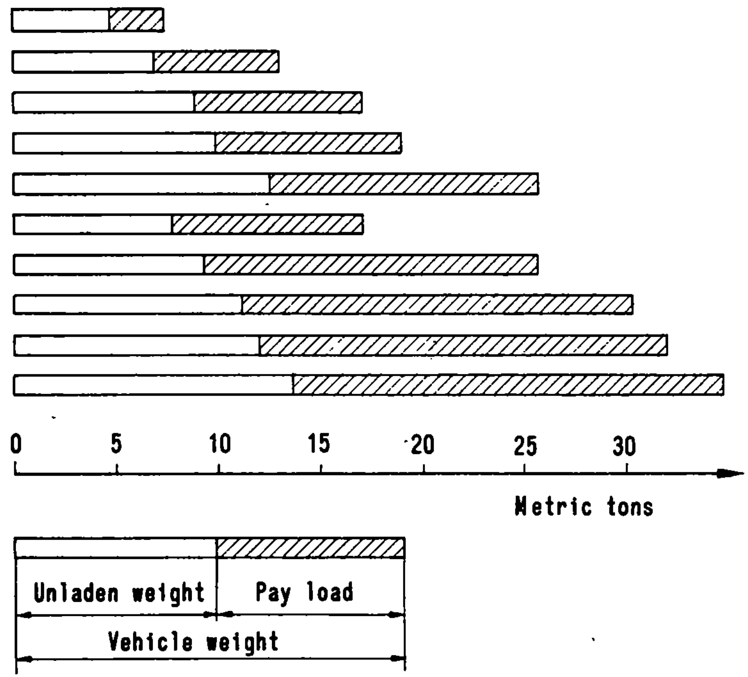
Group of vehicles	Number of vehicles	Per cent	Pay load / Vehicle weight	Mean weights
	9853	60	0.35	
	2107	13	0.46	
	560	3	0.48	
	1363	8	0.47	
	25	0	0.51	
	1122	7	0.54	
	289	2	0.63	
	152	1	0.63	
	1026	6	0.62	
	8	0	0.61	
Total	16505	100		

Figure 14. Number of vehicles, mean weights, etc., in each vehicle group.

Measurements in Progress

In view of the positive experiences gained from these axle load measurements in 1959, the National Swedish Road Board decided early in 1960 that the measurements should be extended so as to cover the whole of Sweden, and should be made regularly at some 200 weighing sites. At the same time, the Board resolved that the manual traffic counts, which had been carried on for many years, should be discontinued for the time being be replaced by these measurements.

Accordingly, the Board requested the Institute to construct new scale equipments. They were improved on the basis of the available experiences so as to increase their reliability in operation and to simplify their handling. The new scale equipment was put into service at the beginning of 1961.

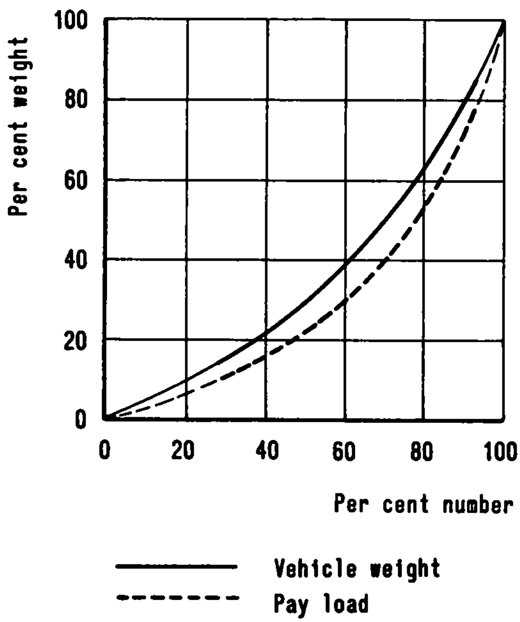
The map of Sweden (Fig. 16) shows the situation of the weighing sites. The country is divided into five regions. The measurements in each region are made by a patrol, which consistes of 2 men, and uses a specially built lorry (see Fig. 17). Each lorry transports three complete scale equipments, road signs, the requisite road-blocking devices, etc. The equipment of each lorry includes, a lifting device used for the installation of the platforms on, and their removal from, the foundations. The measurements are carried out at three neighboring sites at the same time during, say, a week, and then the patrol moves on to the next three weighing sites.

These measurements as well as the evaluation and the analysis of their results are conducted entirely by the National Swedish Road Board. Figure 18 shows lists of traffic count data and axle load data obtained from the data-processing machine.

Estimation of Total Pay Load from Axle Load Data

The estimated total pay load $L_{est.}$ is determined by estimating the total unladen weight $T_{est.}$, which is subtracted from the observed value of the total vehicle weight $B_{obs.}$ measured at the weighing site

$$L_{est.} = B_{obs.} - T_{est.} \tag{1}$$



Group of vehicles	Mean weight in metric tons	
	Vehicle weight	Pay load
2-axle lorry	7,5	2,6
Other lorries and combinations	19.2	9.7

Figure 15. Average relations between weight percentage and number percentage of 2-axle lorries.

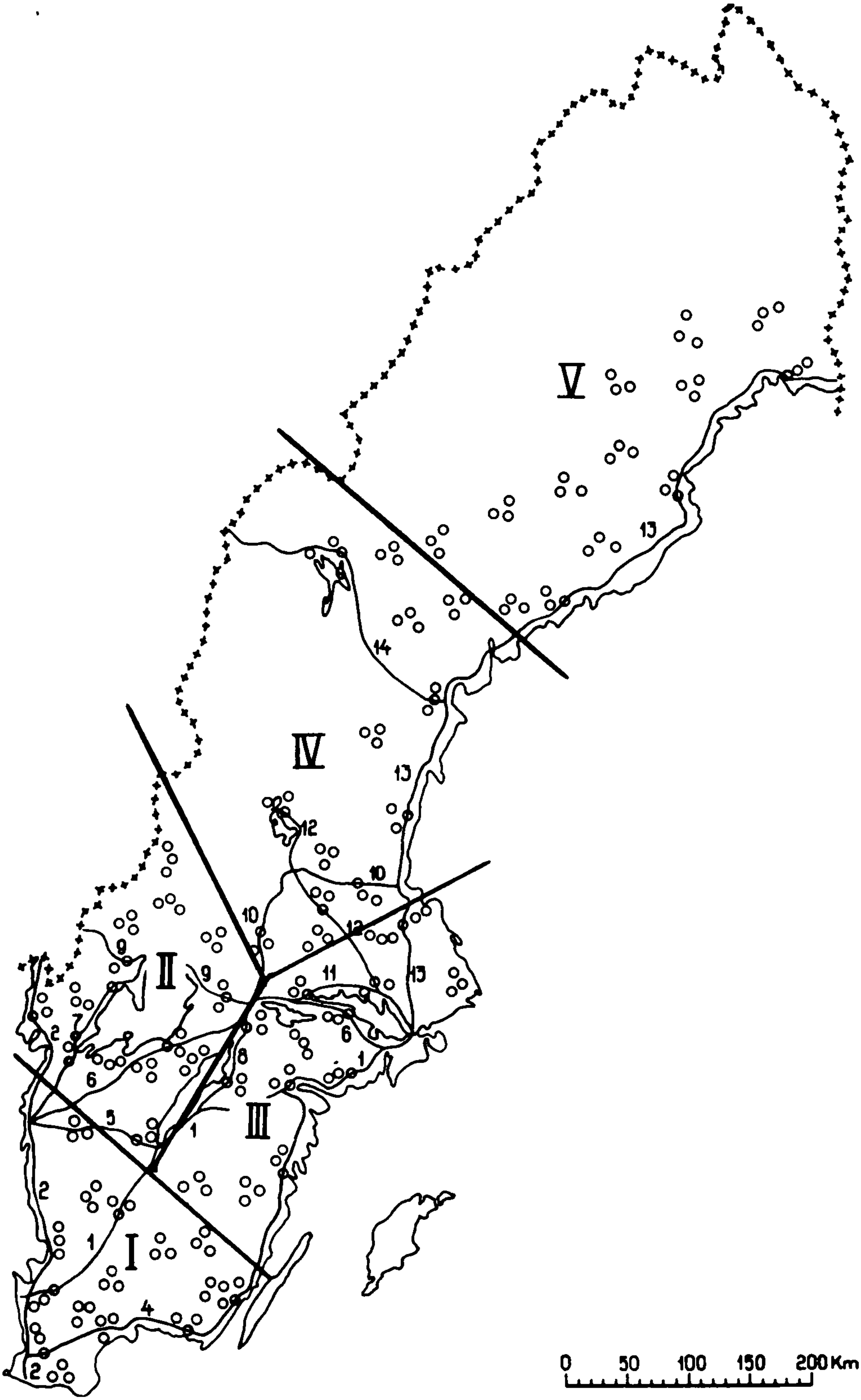


Figure 16. Map of weighing sites in Sweden.

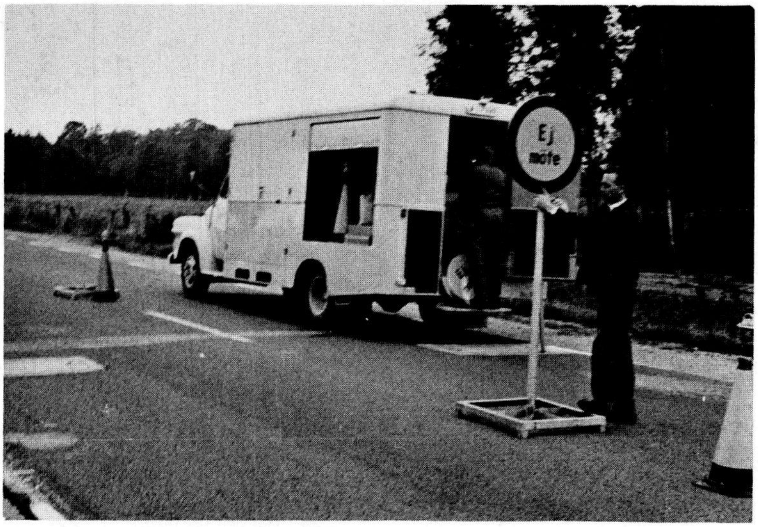


Figure 17. Lorry, specially built for transport of weighing equipments.

A	B	C	D	E	F	G	H	I	ANTAL SINGELAXLAR J AXELTRYCK AV					ANTAL BOGGIE K BOGGIETRYCK AV					ANTAL FORDON L BRUTTOVIKT						
									01 - 04	04 - 06	06 - 08	08 - 10	> 10 ton	01 - 10	10 - 12	12 - 14	14 - 16	> 16 ton	01 - 05	05 - 10	10 - 15	15 - 20	20 - 30	30 - 40	> 40 ton
06	12	1	07	11	3	2	21	3	6										2	1					
						2	22	53	64	21	5		16						10	25	4	14			
						2	34	4	7	7	7		1							2	1		1		
						2	37	4	2	2				1	1			2			1	1	2		

Län A	Plats B	År C	Månad D	Datum E	Vecko F	Rikt. G	Fordons- H	Antal fordon I st	ANTAL FORDON PER TID M RESP. ANTAL (FEL) TIMMAR 00 - 05	05 - 07	07 - 09	09 - 11	11 - 13	13 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 21	21 - 24	N Ton
06	12	1	07	14	6	1	21	12		1	6	1	1	2	1						42
						1	22	43		1	10	6	10	4	5	1	1	3	2		291
						1	33	1				1									3
						1	34	10	1		1		7	1	2	1	2				143
						1	37	1			1										11
						1	41	2		1								1			37
						1	46	5		1		1		1	1		1				55
						1	49	3	1	1									1		63
						1	51	1												1	29
						1	59	1											1		41
								79	2	5											
06	12	1	07	14	6	2	21	5													
						2	22	36	2	7											
						2	34	7													
						2	37	1	1												
						2	41	1													
						2	46	6													
						2	49	1													
						2	59	1													
								58	3	2											
06	12	1	07	15	7	1	21	4		7											
						1	22	38		3											
						1	33	1													
						1	34	2		1											
						1	46	2													
								47		6											
06	12	1	07	15	7	2	21	2													
						2	22	26	1	1											
						2	34	6	1	1											
						2	46	2		1											
								34	2	3											
06	12	1	07	16	1	1	21	1													

A. County
B. Site
C. Year
D. Month
E. Day
F. Day of the week
G. Direction
H. Vehicle type code (fig. 12.)
I. Total number of vehicles
J. Numbers of single axles in different axle load classes
K. Numbers of bogies in different bogie classes
L. Numbers of vehicles in different vehicle weight classes
M. Numbers of vehicles per time interval
N. Total vehicle weight

Figure 18. Results of axle load measurements.

An analysis of the statistical data collected from field studies and from the register of motor vehicles will provide a basis for computing the total unladen weight $T_{est.}$. This analysis is not yet completed. Preparatory investigations have shown that the mean unladen weight $\bar{t}$ in each group of vehicles in Figure 12 is relatively constant. This is in part due to the condition that the heavy lorries, more than about five metric tons in gross laden weight, have in general a wheelbase, l, that is longer than 3.5 m (11 ft 6 in.). The unladen weight of these vehicles is generally about 3 times as great as that of light and medium vehicles having a gross laden weight below about five metric tons and a wheelbase shorter than 3.5 m (11 ft 6 in.). In the axle load measurements, as already mentioned, these two substantially different groups of vehicles are differentiated by means of marks that indicate whether the wheelbase of each individual vehicle is longer or shorter than 3.5 m (11 ft 6 in.). Accordingly, the estimated total unladen weight can be written

$$T_{est.} = n_1\bar{t}_1 + n_2\bar{t}_2 + \ldots \qquad (2)$$

and the estimated total pay load can be written

$$L_{est.} = B_{obs.} - (n_1\bar{t}_1 + n_2\bar{t}_2 + \ldots) \qquad (3)$$

in which

$n_1, n_2, \ldots$ = number of vehicles in the groups of vehicles 1, 2, ... passing weighing site in direction of travel under consideration during a given period of time (numbers obtained from axle load measurements),

$\bar{t}_1, \bar{t}_2, \ldots$ = estimated mean unladen weight in the groups of vehicles 1, 2, ... in a given geographic region.

Estimation of Total Vehicle Weight from Traffic Count Data

A study has been made to find out whether the estimated total vehicle weight of lorries in both directions of travel $B'_{est.}$ can possibly be determined from the numbers of vehicles and the mean vehicle weights in various groups of vehicles passing the weighing site.

This estimate was formed by means of

$$B'_{est.} = n'_1\bar{b}'_1 + n'_2\bar{b}'_2 + \ldots \qquad (4)$$

in which

$n'_1, n'_2, \ldots$ = number of vehicles in the groups of vehicles 1, 2, ... passing weighing site in both directions of travel during a given period of time (numbers obtained from traffic counts),

$\bar{b}'_1, \bar{b}'_2, \ldots$ = mean vehicle weight in the groups of vehicles 1, 2, ... in both directions of travel in a given geographic region (weights obtained from axle load measurements).

The estimated total vehicle weight $B'_{est.}$ was computed on the basis of the data collected from axle load measurements at 29 weighing sites, which were made during the tests on the scale equipments. The percentage ratio of the estimated total vehicle weight $B'_{est.}$ to the observed total vehicle weight $B'_{obs.}$ measured at the same time, $B'_{est.}/B'_{obs.} \times 100$ percent, is shown in Figure 19 for the various weighing sites. The width of each rectangle in this diagram expresses the observed total vehicle weight per weighing site. Each rectangle is marked with a letter indicating the county in which the weighing site in question was situated.

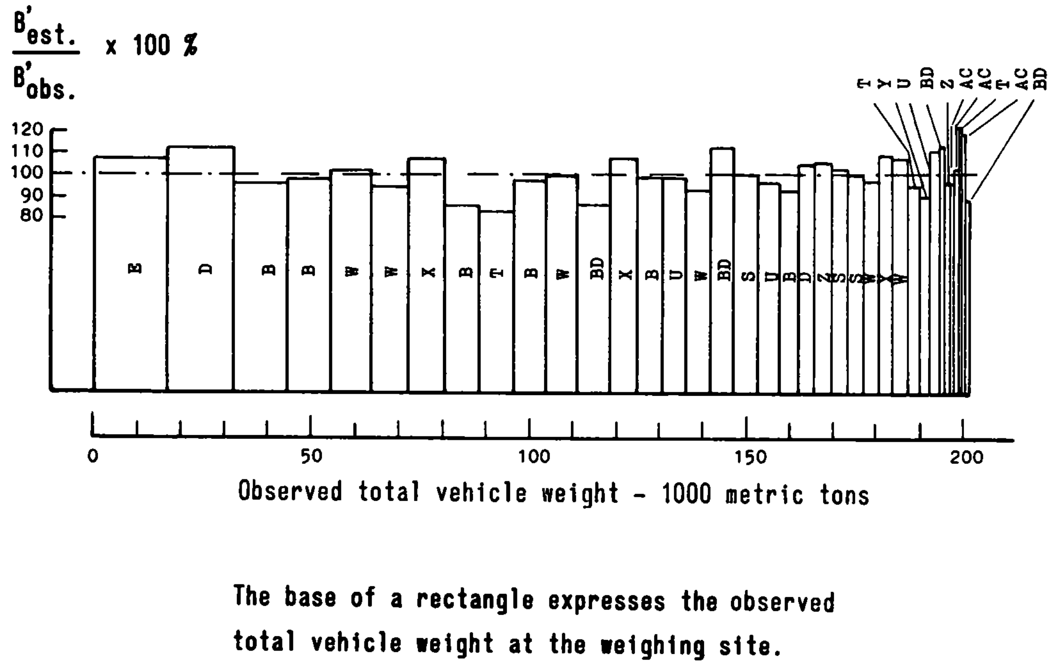


Figure 19. Ratio of estimated and observed total vehicle weight at different weighing sites (letters indicate counties).

Figure 19 shows that the differences between the estimated and observed values of the total vehicle weight are relatively small. Consequently, the total vehicle weight estimated by the aid of Eq. 4 complies with the requirements concerning the accuracy in measurements which need to be fulfilled in determining this weight. The values observed at certain weighing sites in the tests on the scale equipment can involve systematic errors. Therefore, there is reason to suppose that the data based on measurements carried out by means of the scale equipment that is now ready for use will exhibit smaller differences between $B'_{est.}$ and $B'_{obs.}$

Estimation of Total Pay Load from Traffic Count Data

The estimated total unladen weight in both directions of travel is given by

$$T'_{est.} = n'_1\bar{t}_1 + n'_2\bar{t}_2 + \ldots \tag{5}$$

Replacing $B_{obs.}$ by $B'_{est.}$ and $T_{est.}$ by $T'_{est.}$ in Eq. 1 and substituting Eqs. 4 and 5 in Eq. 1 yields an expression for the estimated total pay load in both directions of travel:

$$L'_{est.} = n'_1(\bar{b}'_1 - \bar{t}_1) + n'_2(\bar{b}'_2 - \bar{t}_2) + \ldots \tag{6}$$

This means that the estimated total vehicle weight $B'_{est.}$ and the estimated total pay load $L'_{est.}$ in both directions of travel can be computed if certain constants and the numbers of vehicles in the various groups of vehicles (n'_1, n'_2, ...) are known.

Preparatory investigations indicate that the constants entering into these computations are applicable in large geographic regions.

The number of vehicles in each group of vehicles can of course be counted manually, but this procedure is not appropriate for economic reasons, among others. With a view to enabling these computations to be made with the help of data-processing machines, a vehicle-differentiating traffic counter is being designed at the National Swedish Road Research Institute.

In conjunction with a vehicle-differentiating traffic counter, the methods of estimation outlined can be an extremely valuable aid in traffic measurements, particularly as a supplement to axle load measurements.

Vehicle-Differentiating Traffic Counter

Tests have been made on a prototype of a vehicle-differentiating traffic counter which can determine not only the number of vehicles passing a point of observation in both directions of travel during a certain definite period of time, but also in some respects the types of vehicles. The principles of this traffic counter are based on the fact that the differences in the transport functions of the vehicles are reflected in the number of axles and in the spacing of axles.

Every effort is being made to insure that this traffic counter is small sized so as to be easily transportable. It will be battery operated. It is primarily intended for use on two-lane roads, but its design is such that it can also be employed in a modified form on roads having several traffic lanes in each direction of travel. The results of measurements will be automatically transferred to a tape, and all computations will be made in data-processing machines. The principles of this traffic counter were evolved by the author and by Björn Kolsrud, who is also on the staff of the Institute. Patents covering these principles have been applied for.

General Discussion

VINCENT MCBRIDE, Consulting Engineer, Lebanon, Conn.

• OF THE components involved in highway electronic safety systems the performance and reliability of the electronic equipment is probably better established than that of the passive wiring elements embedded permanently in the pavement.

Valuable experience had been gained in the related field of wiring for flush-mounted centerline lights in airport landing strips over the past several years. With the cost of the wiring material being only about 1 percent that of the lighting units it is unfortunate that inadequate, ordinary wire has been used in a number of installations because the cost of failures and replacement is very high.

A special type of wire designed specifically for the installation and operating conditions involved costs little more than ordinary wire and it has the high degree of reliability that is essential to such systems. When trial installations of highway electronic safety systems are made it is vital that suitable wiring components be used.

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The ACADEMY itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the ACADEMY and the government, although the ACADEMY is not a governmental agency.

The NATIONAL RESEARCH COUNCIL was established by the ACADEMY in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the ACADEMY in service to the nation, to society, and to science at home and abroad. Members of the NATIONAL RESEARCH COUNCIL receive their appointments from the president of the ACADEMY. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the ACADEMY and its RESEARCH COUNCIL thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY-COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.