Electronic Highways

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During the past few years considerable work has gone on in a number of laboratories toward devising equipment to automatically control vehicles on highways or to improve the manual control of vehicles through the use of electronic devices. General Motors Research Laboratories has devised an automatic control system for use with mixed automatic and manual vehicles on limited-access highways. A 1/40th scale model has been built to demonstrate the guidance, obstacle detection, and speed control functions of this system.

Recognizing the transition problem from manual to automatic control, a number of devices have been considered which will provide the driver of conventional vehicles with some aid during the transition period. A communication system, "Hy-Com," using low frequency magnetic induction can provide road sign and emergency information in carefully localized areas along the highway. In addition, a path error warning device has been built which could also utilize a single wire in the roadway to indicate to the driver when his vehicle deviated beyond a safe amount from the centerline of the road. Both of these devices could utilize signals originating in the road wire, which could also eventually serve as a guidance wire in an automatic highway system.

DURING the past few years many investigators have proposed using electronic aids and, indeed, completely automatically controlled vehicles as a means of improving safety and highway transportation efficiency. This paper is concerned principally with a discussion of the design philosophy and construction of a 1/40th scale model of an automatic highway system applicable to limited-access highways. In addition, it discusses the design and application of a low-frequency induction radio communication system and a path error detector, both of which are complementary to the complete automatic highway system and which may be applied as a preliminary step toward completely automatic control.

GENERAL DESIGN CONSIDERATIONS

It is unnecessary here to discuss in great detail the reasons for devising automatic vehicle control systems. Briefly, these are based on reduced driver

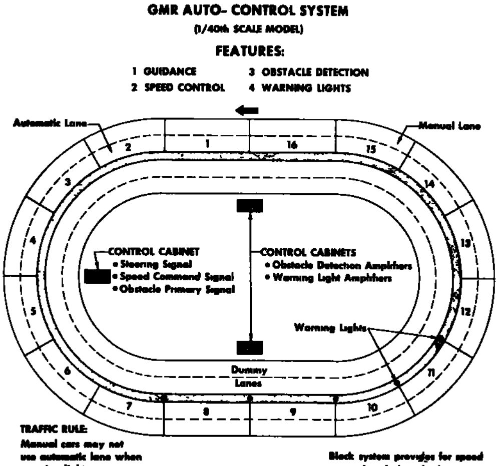


Figure 1. Layout of 1/40th scale highway.

effort and improved comfort, potential safety improvement through elimination of driver error, and increase in highway capacity by eliminating driver lags which influence the spacing of vehicles on present roads. In the development of the GMR Auto-Control System, the concern was only with operation of vehicles on a limited-access highway in order to reduce the complexity of the control system. Even such a limited application could prove practical and useful, however, when it is recognized that some 90 percent of inter-city passenger travel is accomplished in private cars. The transition problem is recognized in this design, and therefore the road model was built to accommodate both automatically controlled vehicles and conventional manual cars. Before discussing the details of operation of this highway model, its general physical arrangement is reviewed.

Essential features of the GMR Auto-Control System are embodied in a scale model

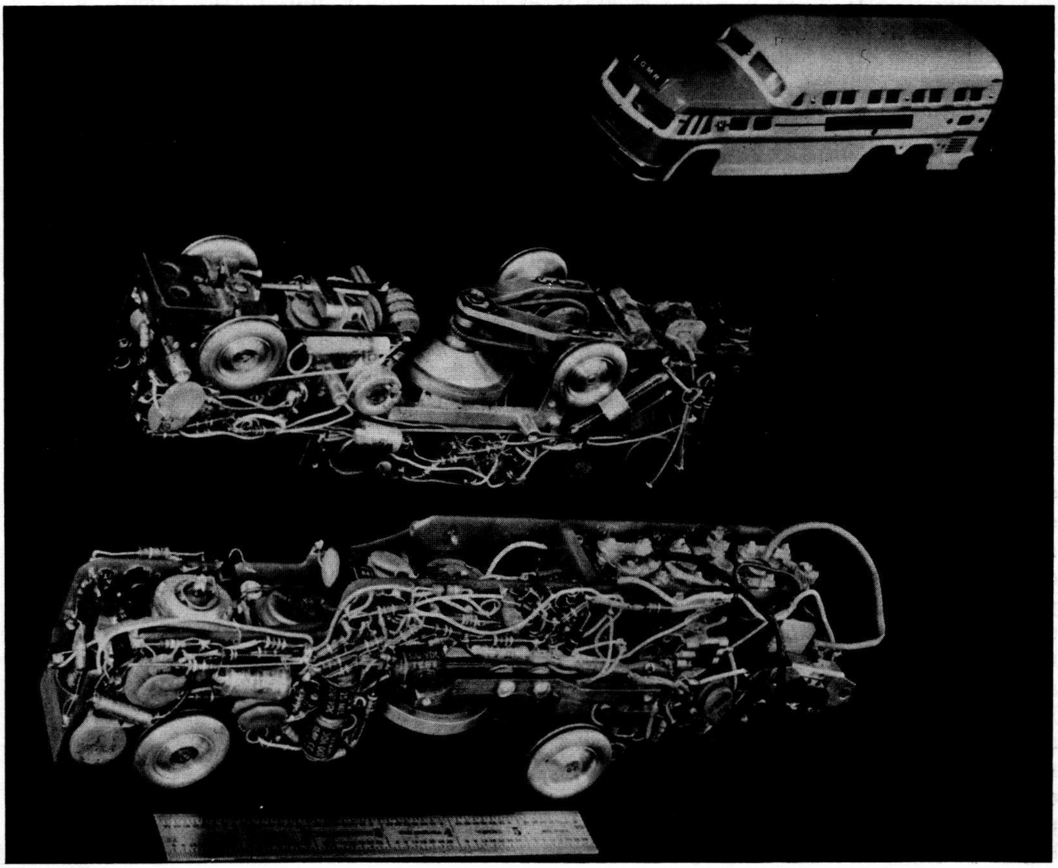


Figure 2. Car-based electronic components.

oval track, approximately 20- by 30-ft over-all, representing a four-lane divided highway. Distances and speeds are $\frac{1}{40}$th scale. The track is made up of sixteen 5-ft blocks, simulating a stretch of highway $\frac{6}{10}$ths of a mile long. At $\frac{1}{40}$th scale, each block represents 200 ft on an actual highway. Suitable wiring is embedded in the blocks to accomplish the various control functions. The general layout of the track is shown in Figure 1. Only the two counterclockwise lanes are equipped for vehicle operation. The right-hand lane has been designated as a manual lane, and the left-hand lane is equipped with sensing and control wiring to provide completely automatic operation of scale model buses. The functions performed automatically consist of:

1. Providing guidance to maintain the proper vehicle path;
2. Detecting obstacles in the automatic control lane;
3. Regulating vehicle speed to prevent collision with other vehicles or obstacles in the automatic control lane; and
4. Providing warning signal lights to control use of the automatic lane as a passing lane for manual cars.

There is clearly a wide variety of means of accomplishing the several functions previously outlined. The particular means adopted for this automatic highway system are considered to be desirable compromises. From the standpoint of ease of transition from manual to automatic control, it would clearly be desirable to have all of the special equipment contained in the car. If neither active nor inactive control equipment were required in the road, vehicles could operate under automatic control on the present road system. On the other hand, there appear to be many shortcomings in such an arrangement, particularly with respect to sensing all of the information required to regulate speed and direction from the vehicle itself. For this reason the control equipment has been divided between the car and the road. In addition, a block system for detection of obstacles and speed control was used rather than a continuous spacing control system for reasons of simplicity and reliability. In fact, a number of design choices involving compromises between reliability and operating efficiency were made in favor of reliability.

MODEL VEHICLES

To provide space for the batteries and electric motors required to drive the vehicles, model buses (Fig. 2) have been used. All of the transistorized electronics sufficient to sense the input signals and provide controls for the power systems of a full-scale car are mounted on two insulating boards which also serve as a frame for the mechanism. An electric torque motor turns the front wheels to provide steering corrections. A silver-zinc battery mounted near the rear supplies power both for the electronics and the drive and steering motors. Additional description of the vehicle details accompanies discussion of the several functions.

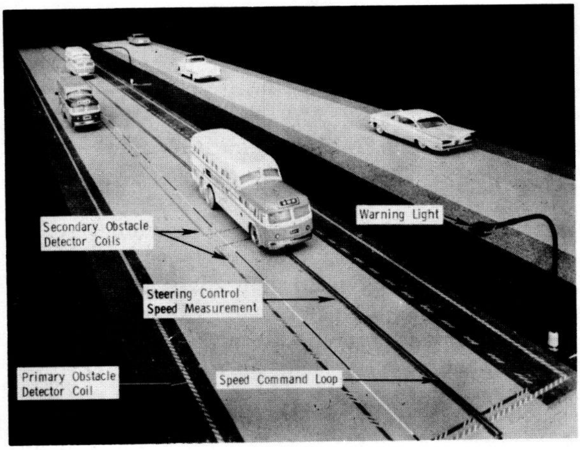
STEERING CONTROL

Providing steering control signals from the road is relatively simple. Because the desired path of the car is the same as that of the road, only the position error of the car on the road must be sensed for guidance. The required steering correction can then be determined, taking into account the car response characteristics in order to assure system stability.

The steering control element in the model highway is in the form of a crisscrossed wire that essentially forms two parallel wires embedded in the pavement down the center of the lane. Alternating current of about 50 kc in the wire generates a magnetic field along its entire path. As pointed out in the following section, this same wire is used for speed sensing. The arrangement of all of the control wiring in one block is shown in Figure 3.

Two pickup coils mounted on the underside of the model car straddle the criss-crossed wire. Changes in voltage between the two coils, as determined by their position relative to the cable, automatically adjust the steering mechanism to keep the car on course. Figure 4 shows the various signal pickup coils mounted on the under side of the small model.

This technique is similar to the electromagnetic system demonstrated on a full-size car by GM Research Laboratories in February 1958. In that system, changes in voltage between the two pickup coils were fed into a small electronic analog computer which directed a servo system controlling the car's steering gear. Similar components within the car are envisioned in any future full-scale version of the GMR Auto-Control System (1).



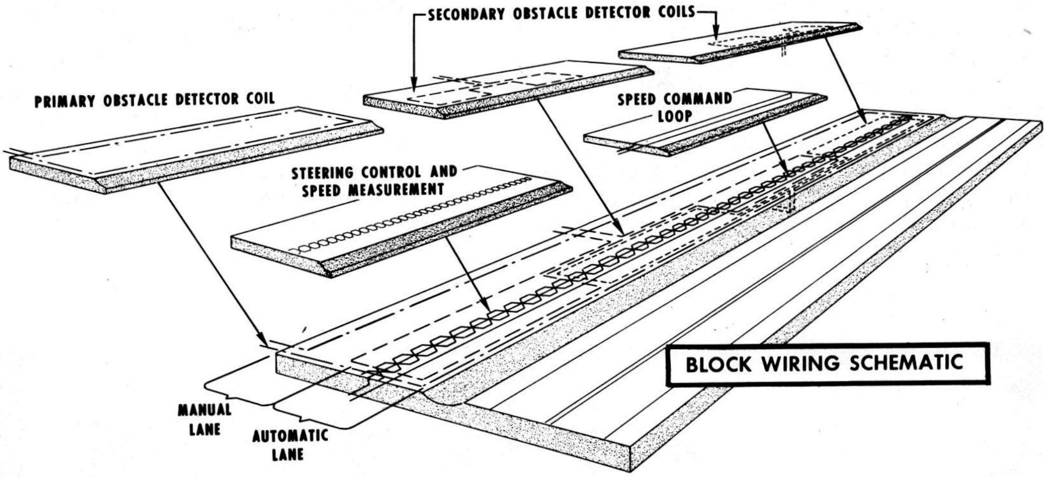


Figure 3. Layout of control wires in one block of the automatic highway.

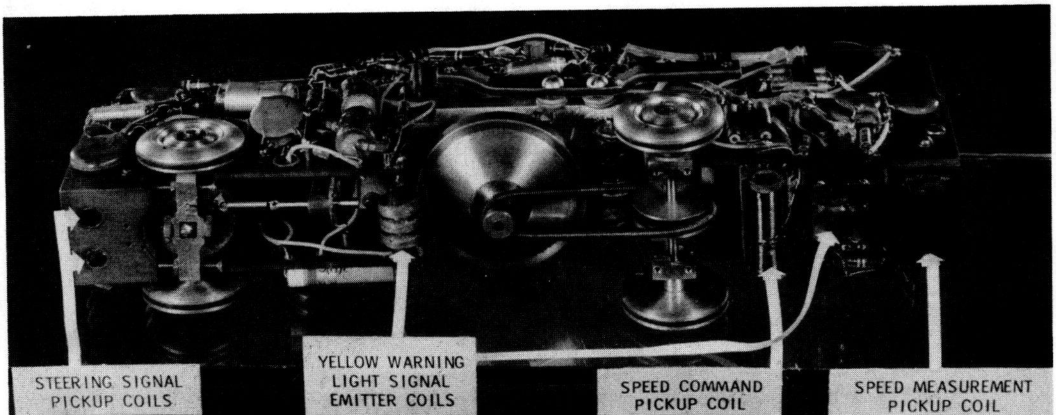


Figure 4. Car-based pickup and emitter coils.

SPEED CONTROL

Rather than permit each vehicle to select its own speed, it was decided that all cars under automatic control should operate at the road speed limit. This eliminates the many passing situations which otherwise develop simplifying the automatic equipment and also prevents delays in the automatic lane due to slow vehicles. Such expeditious handling of automatic traffic is one of the greatest potential virtues of automatic car control.

A scaled top speed of 60 mph was arbitrarily established for the scale vehicles running on the model road. At $\frac{1}{40}$th scale, however, their actual top speed is only $1\frac{1}{2}$ mph. Provision is also made to automatically impose a 30 mph speed limit or to stop the cars completely under circumstances when 60 mph is unsafe. In a full-scale application, any maximum speed could be selected and varied automatically to compensate for changes in vehicle performance depending on driving conditions, for example, wet pavement, ice, or darkness.

Two basic requirements must be met to provide automatic speed control. These are: precise measurement of the car's actual speed, and a speed command signal telling the car how fast it should be going. Any differential between these two quantities can be used to initiate automatic adjustment of the car's speed through control of accelerator and brakes.

The criss-crossed wire is so installed that its two "branches" cross at equally spaced intervals. The voltage induced in the speed measurement pickup coil on the car (Fig. 3) becomes zero at each crossing of the wire, thus providing a definite marker that can be sensed by a pickup coil and counted. The car measures its own speed precisely by a count of the number of voltage nulls passed per second. The cross spacing is selected so that 1 cycle per sec = 1 mph both in the model and full-scale road.

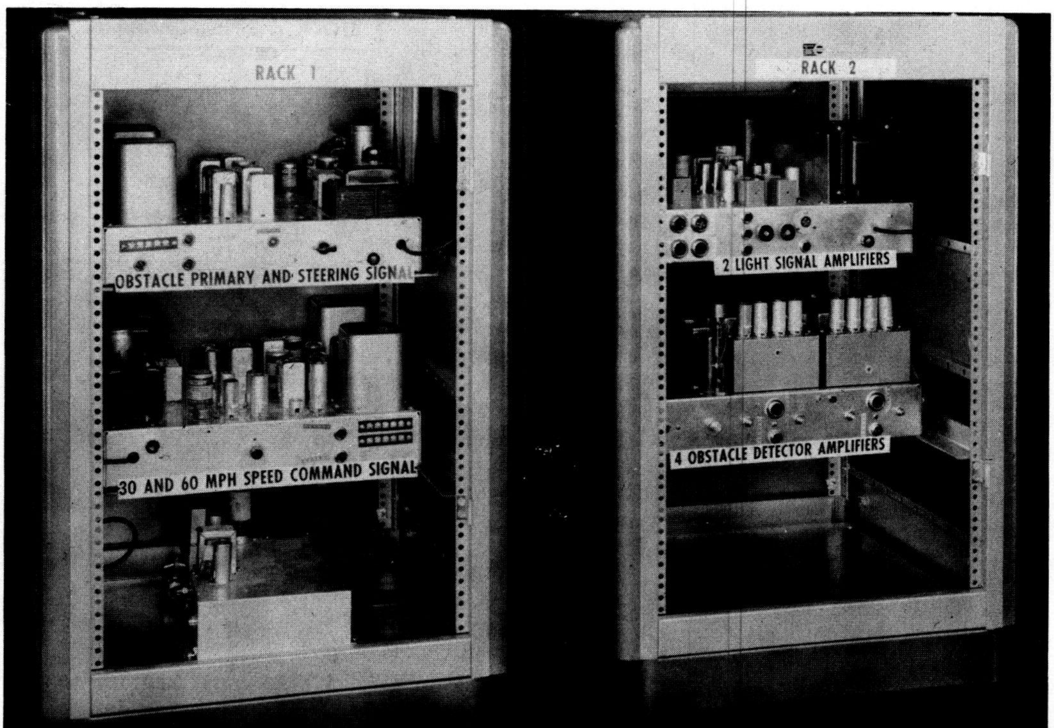


Figure 5. Electronic cabinets for providing signals to the control wires embedded in road.

Another wire, parallel with and centered in the criss-crossed wire, provides a speed command signal that is picked up by another coil on the car. This wire carries a signal of about 90 kc modulated by either of two low frequencies to provide the 60 mph and 30 mph speed command signals. For zero command speed, or "stop," the signal is interrupted. The command speed is determined by the obstacle detectors in adjacent blocks.

If the car's speed is over or under the command speed, an error signal is created proportional to the difference between the frequency of the command speed modulating signal and the number of voltage nulls per second from the criss-crossed wire. The error signal regulates the current to a small electric motor in the model, causing the car's speed to become equal to the road command speed. In a full-size vehicle, this error signal could be used to control the accelerator and brake pedal combination.

The signal frequencies used in the model track are more or less arbitrary values for this particular small-scale application. In a full-scale highway, the actual frequencies used would be dependent on the details of the electronic techniques used.

OBSTACLE DETECTION

The speed and acceleration of individual cars on an automatic highway must be dependent on the position and speed of other vehicles or obstacles on the same road. Therefore, some kind of sensing means is required for determining the relative position and/or speed of other vehicles and objects. It appears that the obstacle detection function must necessarily be part of the road equipment because of certain fundamental limitations in such car-based sensing apparatus as radar, ultrasonics, or infrared (2). The GMR Auto-Control System provides for the electromagnetic detection of vehicles and other metallic objects in the automatic lane only.

Embedded below the surface of each 5-ft block (representing 200 ft on an actual highway) are four obstacle detector coils (secondary) and a larger coil (primary) which encloses the secondary coils (Fig. 3). The four secondary coils are connected in pairs. The two coils in each pair are connected in opposition and are alternately spaced with the two coils of the other pair. Metal objects located in an obstacle detector section have eddy currents induced by the alternating magnetic field produced by the obstacle detector primary coil which is energized with alternating current. This results in a disturbance of the magnetic field through the secondary coil over which the obstacle is located and the resulting unbalance in induced voltage provides a reliable indication of the obstacle whether stationary or moving. The time interval between detection at successive secondaries is also used to give an approximate indication of the speed of the vehicle. Its presence and speed regulate the command speed in following blocks in accord with the following rules.

A car traveling over 30 mph causes a 30 mph (half speed) speed command signal to exist in the first block to the rear and a 60 mph signal in the second block to the rear. A car traveling at 30 mph or below causes a "zero" speed command signal to exist in the first block to the rear and a 30 mph signal in the second block to the rear. Thus, if a car unexpectedly stopped in block 9, for example, the following car would be stopped in block 8, and the next car would be stopped in block 7. If another car were coming up from behind at 60 mph, its speed would be cut to 30 mph in block 5, and it would be stopped in block 6.

To avoid the need for a great deal of road intelligence (with resulting complication) it is proposed that the driver use manual control when fixed obstacles are encountered. The manual lane can be used for getting around the obstacles before resuming automatic operation.

MANUAL CAR OPERATION

In general, drivers of manually controlled cars would drive as usual keeping in the right-hand lane. Their use of the left lane for passing is regulated in the model road by traffic signals which indicate the presence of an automatic car in the immediate vicinity. The warning lights are turned on by a 2 kc signal from a coil on the automatic car to the speed command coil in the road. These lights "travel" along with the car to warn manual cars in the vicinity that the automatic lane is in use. For example, when an automatic car enters block 8, it turns on the lights in blocks 7, 8, 9, and 10. When it enters block 9, light 7 goes off and light 11 comes on. In an actual installation, one light would be installed for each 200-ft block. The signal lights are used to provide smooth operation in the automatic lane but if a manual car entered against a signal it would be detected as an obstacle and cause following automatic cars to stop.

ROAD ELECTRONICS

The electronic equipment racks used with the road model are shown in Figure 5. These are actually representative of functional full-scale road equipment. No particular attention has been paid to reducing size in this prototype. The two cabinets shown provide all of the road electronics needed for 400 ft (2 block) of controlled road with the exception of the primary guidance signal. This signal can be supplied to many blocks by a single simple oscillator. In a full-scale installation this equipment could be installed below grade and operated from batteries floated on a charger to increase reliability.

RELIABILITY

Practical application of automatic vehicle control depends largely on the ability of engineers to produce both mechanical and electronic equipment with adequate reliability. Unless this is accomplished, attainment of improved safety will not be possible.

Redundancy has been used in the Auto-Control model to increase the steering signal reliability. In addition to the crossed guidance wire signal, the speed command wire may be used for this purpose. In a full-scale installation, automatic switchover could occur in the event of loss of primary system signal.

Protection has also been provided in event of speed command signal failure. Loss of command speed is equivalent to commanding zero speed and vehicles in the affected area stop until manual control is assumed by the driver.

TRANSITION PROBLEMS

One of the most difficult problems with regard to automatic vehicle control is that associated with the transition from the present day manual system. This is a particularly difficult problem if it is necessary to provide some of the control equipment in both the highway and the vehicle. It is clearly not economically feasible to either produce vehicles with automatic control systems or to provide roads equipped for this type of operation unless the other is also available. For this reason, it is necessary to consider the steps which might be taken to finally arrive at a completely automatic system. Consideration of this problem has led to some fairly immediate possible steps in this direction. The following discussion is concerned with two possible immediate uses for the guidance wire necessary in a completely automatic system.

HIGHWAY INFORMATION SYSTEM

Communication of information from the road to the operators of vehicles is presently accomplished primarily through visual senses using signs along the road. This form of communication has a number of shortcomings, particularly under circumstances which limit visibility. For this reason, application of a low-frequency induction radio system for communicating information normally found on roadside signs has been considered, along with additional emergency information. Such a system has many advantages, including the ability to readily change the information to suit current operating conditions, and to provide communication within a controlled area without overloading the driver's visual sense and distracting his attention from his control task.

The system is entirely automatic, delivering a message to the driver regardless of whether the car radio is turned on or not. Messages transmitted by the low-power communication system could be in the form of warnings regarding dangerous driving conditions and speed limits, or they might be of the informative type for announcing freeway exits, unscheduled detours, etc. Such a system is shown schematically in

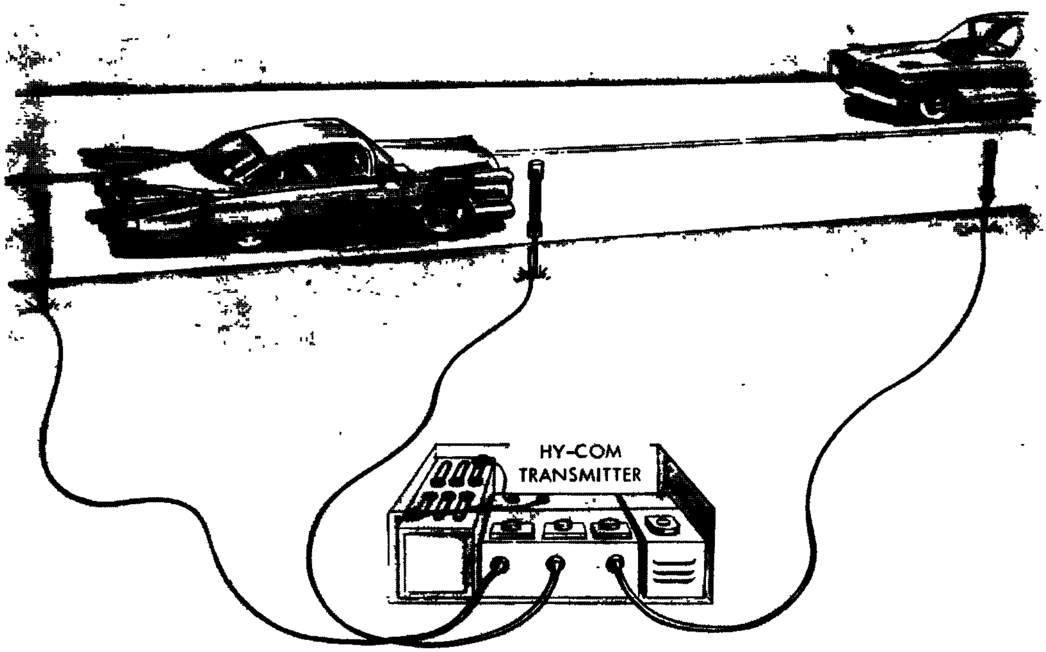


Figure 6. Hy-Com transmitter schematic.

Figure 6. In effect, the system would supplement road signs to give motorists precise instructions relative to the traffic environment, and it would assist police or highway officials in expediting or routing traffic flow.

A unique feature is the voice signal which it is believed would be more effective and flexible than any other type of in-car signal such as buzzers or flashing lights. No array of visual signals would be comprehensive enough to warn a driver of the various emergencies that might arise. A verbal message, on the other hand, could describe any number of situations with instant clarity.

OPERATION

The electromagnetic-induction, low-frequency radio system called Hy-Com, shown in block diagram form in Figure 7, consists of a receiver in the car and a low-frequency transmitter that would be placed alongside the highway. The transistorized transmitter, powered by a 12-volt battery, could be permanently installed above or below ground, or designed as a portable unit for greater application flexibility. A series of individual ferrite core antennas, or a single-loop antenna would be used to cover 300 to 500 ft of roadway. To avoid interference with the many other existing radio communications, the system operates in the 10-20 kilocycle range. And further, by utilizing induction fields instead of radiation, it permits laying down a known and controlled radiation pattern, thereby precluding interference to other services or between adjacent transmitters.

Voice messages can originate from such sources as tape messages repeaters, on-the-spot announcements from microphones, or from a master control station using existing telephone lines. In addition, a coded tone generator could be used to operate automatic warning devices in the vehicle.

Transistors and ferrite loops make possible small, compact transmitter and receiver units. The simple low-frequency receiver may be self-contained and is somewhat less complicated than a car radio. The single-channel, fixed-tuned device uses the standard car radio power amplifier and speaker. The fixed tuned feature insures reception of Hy-Com messages wherever the system is in operation because transmitter frequencies are all the same and not indigenous to locale.

If the radio is operating, the message interrupts the program and the standard broadcast is muted momentarily during the message interval. After the message has been delivered, the standard broadcast is automatically switched back on. When the radio is not turned on, the transmitter signal automatically turns on the car radio transistorized output stage. In the case of a nontransistorized radio, an adapter plug between the radio and speaker permits interruption of the standard broadcast program. General acceptance of the system would dictate that the receiver be incorporated into the standard car radio.

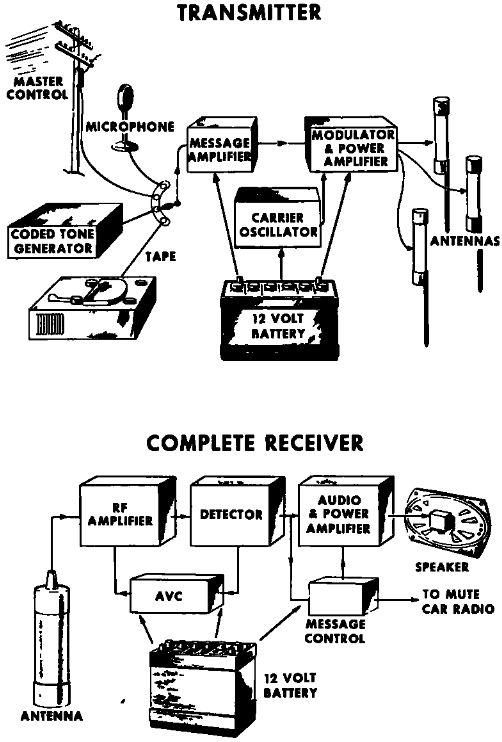


Figure 7. Hy-Com transmitter and complete receiver.

EDGE OF ROAD DETECTOR

Although much work has been done on both components and systems for electronically controlled automatic highways, such roads are undoubtedly relatively far in the future for both technological and other reasons. It seems likely that various devices designed to help the driver better perform his control task will precede completely automatic control systems.

One such device, to provide path error information in manually controlled cars, called "Electro Lane," has already received some development and promises to be a useful adjunct to car instrumentation. This simple device signals a driver when he approaches within a pre-set distance of the edge of a lane or road. It is expected that such a warning would be useful in reducing the large number of single car accidents which occur when driver inattention leads to vehicles leaving their correct lane. In addition, Electro Lane can supplement driver vision under poor visibility conditions and enable a driver to "ride the edge of a lane" at very low speeds.

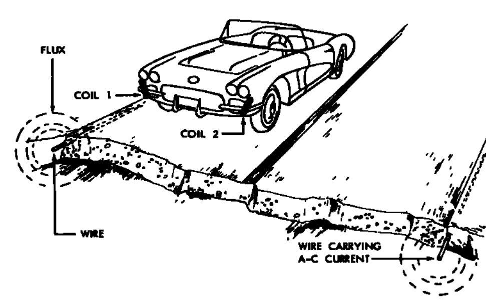


Figure 8. Electro Lane.

A prototype of this equipment has been designed to use magnetic path definition of the same type provided by the guidance wire and sensing coils used to provide automatic guidance both in the auto control model and in full-scale cars. This apparatus can be readily installed on existing vehicles and, in fact, can be designed for temporary attachment to existing cars operated on roads equipped with the required quidance wire. This wire may be installed in existing toll roads and turnpikes at nominal cost or may be incorporated readily in new construction. In existing roads the path error wire may be

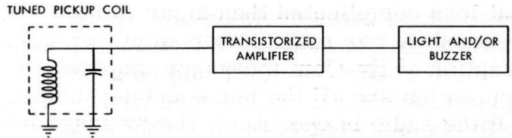


Figure 9. Block diagram of one of the channels used in Electro Lane system.

installed either in a diamond saw cut in the center of each lane or even lower installation costs may be achieved by using wires installed along the road side.

When a wire is used in the center of each lane, path deviation to the right or left may be indicated by mounting two independent detector systems in the front of the vehicle in a manner similar to that used for automatic guidance. If wires are used outside the road lanes, on multi-lane roads, it is not possible to detect the diviion between the two lanes but the road extremities could be indicated as shown in Figure 8. The wires shown are parts of a large loop which could be of the order of 1 mi in length. The loop carries an audio frequency current which induces a circular magnetic field around each of the wires. Motion of the vehicle toward either edge results in an increase in the amplitude of the signal detected by the ferrite cored coil nearest the road edge. When this signal reaches a predetermined value corresponding to a particular distance from the edge of the road, a relay is activated to energize a buzzer, light, or other indicating device. The right and left channels are independent. The warning system in the vehicle must be constructed so as to cause an instinctively correct response of the driver. Fox example, it might be desirable to locate a buzzer indicating too close approach to the left-hand side of the lane in the left-hand side of the passenger compartment. Similarly, the right-hand error signal could appear in the right-hand side of the compartment. Thus the driver would be required to steer away from the indicator. The specific arrangement of the detector coils on the front bumper will be determined by the type of guidance wire provided and by the variation in path which may be permitted. Figure 9 is a block diagram of one of the channels used in the Electro Lane system. The pickup coil is tuned to the road wire frequency. The amplifier is a simple 4-transistor device. The amplified signal magnitude is compared with a reference voltage to provide an accurate signal actuation level.

An additional application of this warning system would appear to be useful on turn-

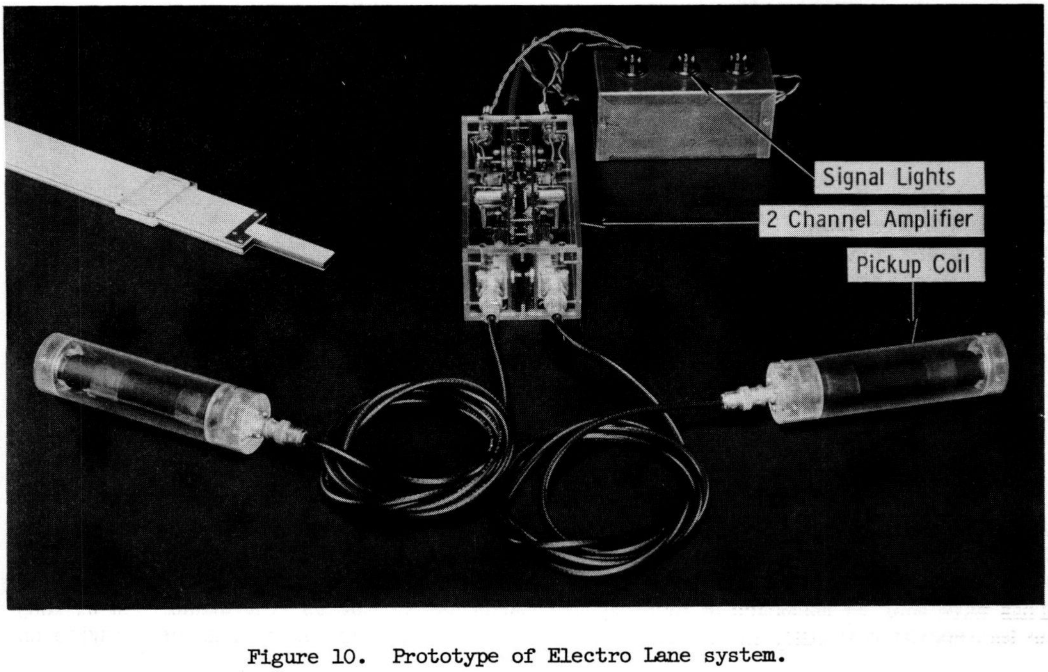


Figure 10. Prototype of Electro Lane system.

pikes. Road wires could be laid crossing the lanes at approaches to toll booths to alert drivers. In fact, the use of such a path error device seems particularly applicable to toll roads where it could be used as a "hang-on" piece of equipment to cooperate with permanently installed road wiring in much the same manner as has been proposed for Hy-Com. Figure 10 is a photograph of prototype Electro Lane equipment which would be suitable for such an application.

CONCLUSION

Although many problems, both technical and non-technical, must be solved before reliable automatic highways can come into general use, the GMR Auto-Control System does illustrate one potentially usable concept. The division of equipment between car and road seems most practical and limitation to operation on controlled-access roads permits retention of reasonable simplicity.

For the immediate future it is possible to utilize a wire in the center of each lane, both for communication to moving cars and in connection with a path error warning system. Hy-Com can make driving simpler and safer by providing audible speed, traffic, and emergency messages to the driver. This system has been further developed by the Delco Radio Division of General Motors. While retaining driver control, Electro Lane can provide a warning to the inattentive operator and help prevent some of the large number of single car accidents.

Both Hy-Com and Electro Lane are particularly appealing for use by toll facilities because they could be readily attached to vehicles using this facility, and can provide road information and path error warning with only a modest amount of road installed equipment.

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