console is extinguished as the MATABE starts the evaluation. Normally, the evaluation is completed and an engagement initiated. However, if there were something faulty with a part of the MATABE concerned with this battery, the resulting error would cause the MATABE to automatically put the battery back into eligibility so that it could be considered, at least, one evaluation period later. These events would be indicated to the cognizant tactical monitor by the extinguishing of the eligibility lamp for that battery for a period of six-tenths of a second, followed by the reillumination of the lamp. However, since most of the time the MATABE would be evaluating battery 21—that is, there are no real batteries available or requiring evaluations—the battery involved in the trouble would be evaluated every other time. The eligibility lamp would thus be lighted for six-tenths of a second and then extinguished for six-tenths of a second. The master tactical monitor would not directly know of this trouble. From his point of view, the MATABE would be operating well, in an over-all sense. However, the cognizant tactical monitor would notice the flashing lamp which would immediately indicate to him the fact that the MATABE was not operating well for his particular battery. Note also, that if an error is of a transient nature—if it is not repeated when the battery is reevaluated—the MATABE causes no indication requiring action or consideration.

During the time that the MATABE is processing battery evaluations, it is also recording a running history of the raid. This record of the raid can be used to help evaluate the performance of the defense system and of the MATABE itself. The significant data for each evaluation are punched out in a 5-bit teletype code while the MATABE is performing the succeeding evaluation. Interlaced

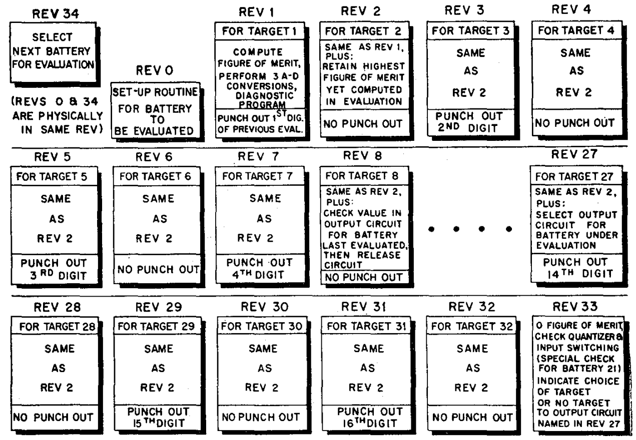

Fig. 4—Instruction program for MATABE battery evaluation cycle.

in the complete cycle of instructions for each battery evaluation is a set of instructions indicating the moment to punch out each digit of data concerning the previous evaluation. The manner in which this is accomplished is indicated in Fig. 4, which also effectively summarizes the entire MATABE computational routine. The various aspects of the MATABE's position in the over-all system stem from the sequence of instructions in drum revolutions 0-34.

We hope that the foregoing has given a fairly broad, but comprehensive, picture of the operational aspects of the Multiweapon Automatic Target And Battery Evaluator which is probably the first large-scale digital computer whose design was tailored to effect a real-time control function.

Control of Automobile Traffic—A Problem in Real-Time Computation*

D. L. GERLOUGH†

Introduction

AUTOMOBILE traffic in urban areas has been characterized as one of our most serious engineering problems.[1] Fig. 1 to Fig. 3 show respectively for one particular area the recent increases in population, motor vehicle registrations, and motor vehicle registrations per person. Some urban areas have approached the traffic problem by the construction of a network of superhighways or freeways. In other areas a solution has been sought through improved traffic controls on existing streets. But in many cases traffic continues to grow more rapidly than corrective measures can be provided. The question is frequently asked, therefore, "Can we improve traffic movement by some control system which takes ad-

* The opinions expressed herein are those of the author.

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[1] H. E. Wessman, "What are contemporary demands on the engineering curricula—civil engineering," *J. Eng. Educ.*, vol. 43, pp. 298-302; January, 1953.

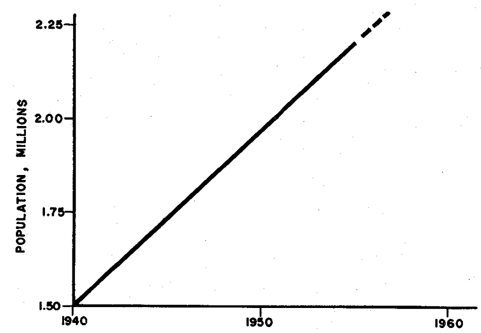

Fig. 1—Population growth, City of Los Angeles.

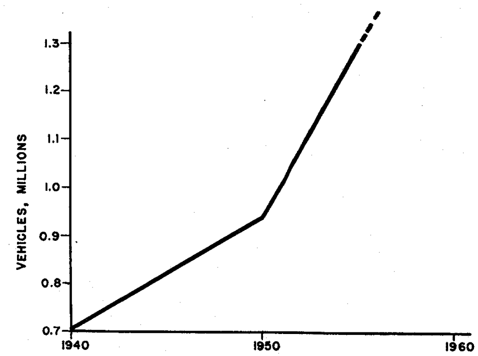

Fig. 2—Motor vehicle growth, City of Los Angeles.

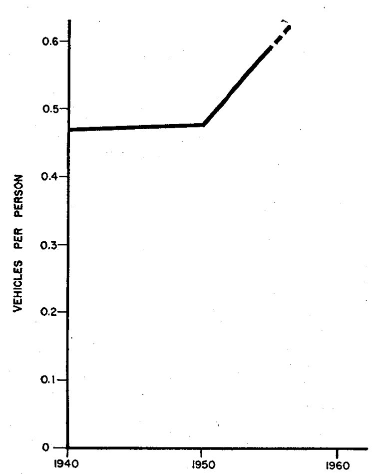

Fig. 3—Increase of vehicles per person, City of Los Angeles.

vantage of the abilities of the large-scale automatic computer?" It is the purpose of this paper to discuss some of the possibilities and difficulties involved.

Area Control of Traffic

In approaching this problem the engineer sees a control spectrum. At one end, control is accomplished by supplying advisory or mandatory instructions to the driver, who, in turn, executes control orders. At the other end of the spectrum, control might be made fully automatic with the driver playing no part as long as the vehicle remains within the control system. For the purpose of this discussion these extremes will be designated "the manual system" and "the automatic system."

Manual System

In the manual system, control consists of gathering information on present traffic, comparing present traffic with stored information on past traffic behavior, and supplying information to the drivers as to how to proceed. An example of a crude form of this type of control takes place annually on New Year's Day in Pasadena, Calif., where extremely large crowds gather for the Tournament of Roses Parade and football game. For several years it has been the practice of the Chief of Police to take to the air in a blimp or helicopter carrying police radio equipment. On the ground, police cars are stationed at strategic control points. By observation from the air it can be determined which thoroughfares are overloaded, and which, if any, can carry additional flow. This information is used as a basis of radio commands to the various control points to cause diversion of traffic from overloaded to underloaded thoroughfares. (The police officers give instructions to the drivers who control the cars. Here instructions are mandatory.)

The City of Los Angeles for nearly two years has had a helicopter which is used primarily for freeway control during the rush hour periods. Observations are made of tie-ups or potential tie-ups and corrective action is taken. Where a tie-up occurs, information is sent to other drivers via radio advising them to take a different route.

Several cities have been experimenting with closed-circuit television as a means of obtaining information on traffic behavior. It is not inconceivable that information in the form of maps, etc., might be transmitted to the driver by television.

Thus, with manual control, one of the principal techniques is diversion of traffic from overloaded to lesser loaded thoroughfares.

Another technique is the control of traffic signals on an area-wide basis. In Denver and Baltimore, there have been approaches made to the control of traffic signals in the city as a whole on the basis of the traffic actually present. These approaches have, however, been based on a limited number of sampling points, a limited number of control possibilities, *e.g.*, signal cycle lengths, and communication with the driver solely on the basis of conventional traffic signals.

To obtain the maximum benefit from control of traffic on an area-wide basis with the manual system, it will be necessary to have many sampling points, several forms of communication with the driver, a large stored background of information on traffic behavior within the area, and a large central computing facility. Stored information must include anticipated origins and destinations of traffic as a function of time of day and day of week. Unusual patterns on occasions of special events must also be known. Characteristics of the complete street network must be stored in the forms of lists of parameters. Most important of all, there must be information in the form of equations, curves, or simulation procedures which will permit the computation of the flow behavior on a given thoroughfare under varying conditions. The central computer will evaluate the existing situation and select the appropriate control measures.

Traffic signals of the conventional type will still constitute an important communication channel between the system and the driver, but other forms of communication will play an increasingly important role. There may be wide usage of changeable signs to convey special messages to the driver at appropriate times. For instance, neon signs, similar to those used on some of the Eastern turnpikes to inform drivers of snow, ice, etc., may be used to inform the driver of changes in turning regulations, direction of flow on one-way streets, closing of streets, etc. In many locations even a series of neon signs may prove to be too inflexible, and a sign made up of individual lights may be needed. This sign could display a moving message similar to that used to convey the news at Times Square in New York, or more likely as a sign of similar type construction but with the message not moving. Such signs can be remotely controlled by a computer. Radios can become an increasingly important method of communication to the driver, and it is conceivable that the use of radio might be mandatory for the driver just as radio is mandatory for the flyer who wishes to make use of certain airports and certain air navigational facilities.

Traffic can be sensed by the techniques to be described in connection with the automatic system.

To summarize: In control by the manual system, operation is manual only in that the actual driving of the vehicle is manual. Selections of routes, etc., are performed by the central computer. Benefits will come through the diversion of traffic to various routes so that the load is spread more uniformly, and through the use of extremely flexible signal timing.

Automatic System

In an automatic system the driver does not have direct control of the vehicle and there are many ways in which marked improvements in traffic flow may be obtained. Fig. 4 shows the form of curve relating the number of vehicles per mile in a traffic lane and the number of vehicles which can flow per hour in that lane.

It will be noticed that at the peak capacity there are only about 2000 cars per hour traveling per lane at a density of around 100 cars per mile. In other words, under present traffic situations, the amount of unused space in the traffic stream is appreciable. The drop off from the maximum flow occurs by virtue of the fact that drivers must maintain increasingly larger spacings as speeds increase. If some method were devised whereby vehicles could be operated close together without danger of collision, it might be possible in an extreme case to operate as high as 264 vehicles per mile with no change in spacing as speeds increase. For instance, Le Tourneau[2] has indicated a technique for coupling of long trains of vehicles to be operated on normal streets and roadways. It seems doubtful, however, that the motorist would ever accept an actual coupling of vehicles, but if a method were achieved by which vehicles could be operated more closely at least on roads of a freeway type, considerable economy would result. Close operation necessarily implies, however, operation of all vehicles at approximately the same speed. It is possible that drivers might accept traveling at a uniform speed if the benefits achieved thereby were quite clear.

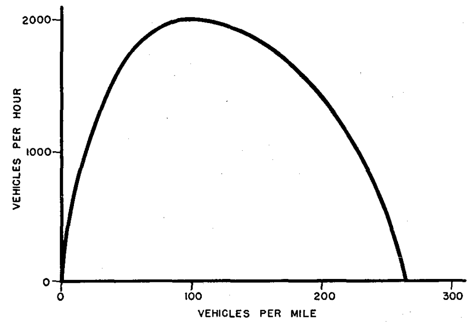

Fig. 4—Form of density-volume relationship for single traffic lane.

Zworykin and his associates, on the other hand, have demonstrated by means of a model a method by which vehicles follow a buried conductor and in which speeds can be different for different vehicles, passing being permitted.[3] The guidance principle of the buried conductor has been demonstrated for full-scale usage by a vehicle designed for use in the arctic.[4]

From the standpoint of optimum control it would be desirable to maintain a continuous record of each vehicle in the system. The computing task involved, however, would be so large as to dwarf several SAGE systems, and thus it does not appear that this would be feasible. Instead, as much of the control as possible should be carried in the individual vehicles. One might visualize, then, that the ultimate achievable control system would contain some sort of guidance, by buried conductor or otherwise, including collision prevention and automatic provision for passing as the vehicles come too close together. There should be provision for automatically selecting the optimum routes to various portions of the area on the basis of the traffic pres-

[2] "Trackless cross-country freight train has all-wheel drive," *Elec. Eng.*, vol. 75, p. 95; January, 1956.
[3] "Possibilities of electronic control of automobiles explored by Dr. Zworykin," *Elec. Eng.*, vol. 72, pp. 849-850; September, 1953.
[4] C. O. O'Rourke, "Electronic trail-finding," *Control Eng.*, vol. 4, pp. 117-119; May, 1957.

ent and the amount of traffic going to each zone. Each driver on entering the system could, for instance, set a destination indicator in his vehicle. This could be a tap switch which would select a signal to be emitted from his vehicle and picked up by appropriately placed scanners on the roadway. These scanners would count the number of vehicles going to a given zone, and a computer would select the appropriate routing accordingly.[5] As routings were computed, optimum exits for each zone would be established for the current amount of traffic. On approaching the designated exit for the particular zone of destination, the vehicle's emitted signal would be sensed, and the vehicle would be automatically guided to the deceleration lane leading to the exit. Here the automatic control would cease and manual control would begin. The manual system has the advantage of a much lower cost in that it makes use of the computing and control facilities of the human operator; it does not necessitate reconstruction of the existing highways to provide the facilities necessary for fully automatic control. It can thus be accomplished at an earlier date and accomplished in a stepwise fashion.

The principal benefit from the automatic system is, then, increased flow (*i.e.,* increased capacity) on a given facility. A fringe benefit will be the decrease in tension on the part of the drivers on being freed of the driving task within the freeway system.

System of the Future

If, then, one may be permitted prevision, an urban traffic system in the year 19XX may be something like this: Long distances will be traveled on a system of freeways where control will be conducted in the automatic mode. Entrances and exits of these freeways will connect with one-way streets where parking is prohibited; these streets will serve as the carriers for intermediate distances. On these intermediate streets control will be conducted in the manual mode; drivers will receive instructions by means of traffic signals, special signs, and radio. Between these intermediate thoroughfares there will be "local" streets on which there will be no central control. That is, the driver will have complete control subject only to conventional traffic signals.

The automatic-control equipment will consist of units carried by each vehicle, sensing units located at appropriate points throughout the street network, and a central control unit containing a computer.

Vehicular Units

Each vehicular unit will contain: 1) the destination indicator composed of a signal generator, a selector switch, and the appropriate radiation equipment, 2) automatic tracking and control equipment to permit following a conductor in the pavement or other guidance, including facilities for passing and for collision prevention (while collision prevention will be mainly in the automatic mode, provision can be made to permit its use in the manual mode as well), and 3) radio equipment, either a standard AM receiver or a special receiver for control messages.

[5] To avoid confusion and disruption of such a system by visiting vehicles, visitors would be required to stop prior to entering the system to pick up a map and code sheet so that they could properly adjust their destination indicators.

Sensing Units

Sensing units will have the ability to determine for each passing vehicle its presence, speed, and destination. The destination will be ascertained, as previously stated, by sensing a driver-selected signal emitted from the vehicle. The sensing unit will have the ability to accumulate data for later transmission via digital data link on receipt of an interrogation signal.

Central Control Unit

The central control unit will have a programming device which periodically interrogates the various sensing units. Origin and destination information for the traffic in the system will be continuously accumulated with appropriate updating.

There will be stored, probably on some random-access large-capacity medium, information on past origin-destination movements; information to be stored could well include such items as time of day and rate of onset for particular flow patterns, and the optimum handling of these patterns. Special provisions for emergency situations such as diversion of traffic from disaster areas could be provided for in advance. To aid in the compilation of this stored information it would be desirable for the computer to possess learning ability. One computer can serve both the automatic and manual portions of the system, or there can be a separate computer for each portion with intercommunication between the two.

The computer will continually compute control parameters on the basis of the origins, destinations, volumes, and speeds of existing traffic by means of analytic relationships or simulation routines. These parameters will provide a basis for searching the stored body of knowledge in order to find the appropriate listing of optimum control procedures. These procedures will be read from storage to the control transmitter which will cause them to be executed. As vehicles pass various exits of the system exit data will be fed back to the computer as a check on performance.

Development of System

Such a system cannot, of course, spring into existence full grown. It must be built in a piece wise fashion over a number of years. While much of the computer technology is presently at a stage which would permit the immediate start of design, much research and development will be required in other phases of the problem.

One thing which needs to be decided early is the form of guidance to be used. This information should be made available at the earliest possible date to the designers of new freeways and automotive equipment. It is visualized that there might be a long transition period in which some vehicles would be equipped with guidance facilities and others would not. It would be necessary to set a date after which no new vehicles would be sold without guidance facilities and a still later date beyond which no vehicle would be allowed to use a freeway-type road unless so equipped.

Systems of intermediate streets should be developed as rapidly as possible and can provide immediate relief to certain existing situations.

Research Needed

The area requiring the most investigation is the formulation of relationships describing traffic flow and indicating the measures for optimization. While progress is being made in theoretical investigations by Lighthill and his associates at the University of Manchester,[6] Richards,[7] Prager and Newell at Brown University,[8] Edie and others at the Port of New York Authority,[9] the staff of the Chicago Area Transportation Study,[10] and Pipes at the University of California,[11] there is at present no comprehensive theory of traffic flow. To bridge this lack of theory, development of traffic simulation techniques has been undertaken at the University of California by the writer and others,[12] Goode and others at the University of Michigan,[13] Wong,[14] and the staff of the Road Research Laboratory in England.[15]

Paradoxically, while traffic is a very important and complex engineering problem, the amount of high-grade technical talent applied to this problem has been exceedingly small in comparison to the technical skills required for the development of a single large-scale weapons system. There are few agencies conducting continuing research in problems related with the possible use of computers in large-scale traffic control systems. To the best of the writer's knowledge, all efforts to date have been supported by rather limited budgets. If there is to be any major change in the handling of traffic, such as that visualized in this paper, there must be early recognition of the need, and the appropriation of adequate funds by both public agencies and commercial interests so that the needed research and development may be accomplished in time to permit an evolutionary change.

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[8] W. Prager, "On the Role of Congestion in Transportation Problems," Div. Appl. Math., Brown Univ., Providence, R.I.; March, 1955.

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[11] L. A. Pipes, "A Proposed Dynamic Analogy of Traffic," Special Study, Inst. Trans. and Traffic Eng., Univ. of Calif., Los Angeles, Calif.; July 11, 1950.

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D. L. Gerlough, "Simulation of freeway traffic by an electronic computer," *Proc. Highway Res. Board,* vol. 35, pp. 543-547; 1956.

[13] H. H. Goode, C. H. Pollmar, and J. B. Wright, "The use of a digital computer to model a signalized intersection," *Proc. Highway Res. Board,* vol. 35, pp. 548-557; 1956.

[14] S. Y. Wong, "Traffic simulator with a digital computer," *Proc. WJCC,* pp. 92-94; 1956.

[15] Several unpublished technical memoranda.

Discussion

J. L. Jones (Chrysler Corp.): From your paper, I received the impression that most of the work done has been on traffic pattern recognition to which an already known solution may be applied. If this is true, has any work been done on a mathematical model to which analystical processes may be applied?

Do you advocate that automotive manufacturers consider future inclusion of a "traffic control radio" as standard equipment? If so, what should the salient features of such equipment be?

Mr. Gerlough: Work is being done on mathematical models, but it is progressing slowly. Many of the investigators are in universities and have not had budgets to cover this type of work. In recent months there has been some interest shown by one of the automobile manufacturers, and it is hoped that this will result in an increasing rate at which mathematical studies progress.

Yes, I would advocate such a radio as standard equipment. The specifications should be worked out by some national committee which should include representatives of automobile manufacturers, highway people, and the FCC.