Simulation of Freeway Traffic by an Electronic Computer[1]

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The electronic computer offers promise of becoming a powerful tool in studying the flow of traffic on freeways. To program such a problem for the computer the engineer must quantize time and distance. For input data he must have as a minimum a distribution (measured or assumed) of desired speeds and a distribution of input time-spacings. Additional phenomena which may be handled include vehicle length, following practices, passing practices, and time within system. For the treatment of such problems there are available two markedly different approaches each of which is discussed.

Exploratory studies indicate qualitative agreement between results and expected behavior.

THE purpose of stimulation on an electronic computer is the experimental determination of phenomena which are too complex to study analytically and which may not be conveniently studied empirically in the real-life situation. Simulation provides, in many cases, a method of accomplishing at high speed, logical manipulations which might be carried out by pencil and paper but which would be so tedious as to become prohibitive. One of the basic tenets of simulation is the introduction of random processes into the behavior of the system under study.

In a paper (*1*) presented at last year's meeting of the Highway Research Board it was shown that problems of traffic flow at intersections and in networks of intersections might be usefully treated by several simulation techniques using electronic computers. In another paper, Goode and his associates (*2*) at the University of Michigan describe a study in which an experimental run was made on a general-purpose digital computer at the University of Michigan. Both of these studies were limited in their scope to intersection problems in which the vehicles approached generally within a single lane and at uniform speeds. It is the purpose of this paper to discuss simulation of the movement of vehicles on open highways where traffic may move in several parallel lanes and at widely varying speeds. In order to relate this study to urban situations the problem to be studied has been considered one of freeway operation.

[1] Based on the author's dissertation, "Simulation of Freeway Traffic on a General-Purpose Discrete-Variable Computer," submitted in partial satisfaction of the degree Ph.D. in Engineering, University of California, Los Angeles, June 1955.

GENERAL-PURPOSE COMPUTERS

While special-purpose computers might be designed for treatment of the freeway problem, the techniques to be described herein are applicable to a general-purpose digital computer. A general-purpose computer is normally designed to handle arithmetic operations. When other types of manipulation are to be performed, they must be accomplished by appropriate combinations of arithmetic operations. Most large-scale automatic computers are designed to handle numbers in binary form. Within the computer, numbers are stored in positions known as memory cells. Numbers are withdrawn from the appropriate memory cells, operated upon, and returned to the same or different memory cells by a series of commands collectively known as a routine or code.

MODEL

The first step in any simulation program is the formulation of what might be called the rules of the game; the mathematician or physicist calls this the "model." This model may be either sketchy or in great detail, depending upon the desires of the experimenter. In the study to be described here, the model may be stated as follows:

1. Vehicles enter the system with some known distribution of time spacing. (This distribution may be either theoretical or derived from field observations. With either theoretical or measured distributions the time spacing data may be prepared outside the machine and fed in as required. If the distribution is theoretical, the machine may be asked to generate the data internally as part of the simulation routine.)

2. It is assumed that there is a known distribution of desired speeds for vehicles entering the system. It is assumed that no vehicle travels in excess of its desired speed but at times may be required to travel at less than its desired speed by virtue of blocking by slower vehicles ahead.

3a. It is assumed, generally, that vehicles will stay in the right-hand lane. If, however, the vehicle should encounter a slower vehicle ahead, the faster vehicle may move into the lane or lanes to the left, pass the slower vehicle, and return to the right-hand lane, subject to any conflicts which may exist As part of the encountering and passing operation it is necessary to assume or define some minimum safe following distance. This may be either a constant or a distribution. If a distribution is used, the distance may be made a function of either speed or of a random variable.

3b. Vehicles are assumed to proceed at some particular speed until they encounter a vehicle ahead in the same lane. Encountering is said to take place where the faster vehicle is so close to the slower vehicle ahead of it that permitting movement to continue for one more unit of time would result in the faster vehicle becoming too close to the slower vehicle ahead. When encountering takes place, the rear vehicle must check the lane to its left to determine if passing may be safely accomplished. If such is the case it moves into the left-hand lane and proceeds to pass, subject, of course, to restrictions caused by any slower vehicles it may encounter in this left-hand lane. If because of blocking of the left-hand lane by the presence of other cars parallel to, too close in front of, or too close behind the car which desires to pass, the car may not pass but must instead decrease speed (perhaps in a stepwise fashion) to the speed of the slower car ahead.

3c. After a faster vehicle passes a slower vehicle it examines the lane to the right to determine whether pullover may be accomplished.

4. To permit handling of movement by the computer it is necessary to quantize distance and time. (Care must be exercised in selecting these units. If the units are too small, the computational work required may be excessive. If the units selected are too large, there may be inadequate representation of the phenomena under consideration.) As a result of quantizing distance and time, speeds will also be quantized. (The lengths of vehicles are expressed as integral multiples of the unit length.)

5. During each unit of time, vehicles which are travelling at less than their desired speeds will check for opportunities to increase their speeds by virtue of obstructions having been removed.

FORMS OF REPRESENTATION

In using this model for simulation on a general-purpose computer, two broad types of approach exist: One method consists of representing vehicles by "1's," singly and/or in groups, in a binary number and the spaces between vehicles by the "0's" in the binary number, as shown in Figure 1. These "vehicles" are then caused to "flow" through the computer in a manner which will simulate the movement of traffic. The second technique consists of representing all of the conditions pertaining to a given vehicle by a code word or number, the parts of which can be extracted and interpreted by suitable computer routines. These two techniques may be designated physical representation and mathematical representation, respectively.

For purposes of simulation by physical representation techniques, the roadway may be considered to be made up of several memory cells laid end to end. Forward movement may be accomplished by any mathematical operation or group of operations which causes the

0 0 0 1 1 1 0 0 0 1 1 0 0 0 0 1 1 0 0

Figure 1. Representation of vehicles by binary digits.

binary digits representing vehicles to move in a forward direction within any given memory cell and, on reaching the boundary of a memory cell, to move across into the next cell, if so required by continuation of the roadway.

FORWARD MOVEMENT

In binary arithmetic it is indicated that multiplying any given value by a power of two, shifts the value to the left by the number of places corresponding to the exponent of the power. Thus, multiplications may be used to produce the phenomenon of forward movement if the direction of forward movement is taken to be from less significant to more significant ends of the memory cells representing the roadway. Since any given channel may be made up of several memory cells, digits which pass through the more significant (left) end must be added to the less significant (right) end of the memory cell which represents the next section of the channel. To understand the manner in which this may be accomplished it must be remembered that, in general, multiplication of any two factors results in a product which has twice as many places as the two factors. Figure 2 shows how forward movement of b units is produced by multiplication by 2^b. The partial products resulting from the contents of cell 1 go to cells 11 and 21, the more significant partial product going to cell 21 and the less significant going to cell 11. Likewise the partial products of the contents of cell 2 go to cells 12 and 22, etc. Cell 20 contains all zeros. The contents of 20 and 11 are added and placed in cell 1; likewise the sum of the contents of 21 and 12 is placed in cell 2, etc. Thus, following the procedure shown in Figure 2, it is possible to combine the results of a series of multiplications to give the effect of moving a line of binary "1's" as though they were a unit even though they may be distributed over several memory cells.

In the case of physical representation, the record-keeping required to keep track of vehicles which have desired speeds of some given value but which may be travelling at any of several lesser speeds requires special treatment. This may be accomplished by using for each traffic lane not one series of memory cells but many series of memory cells, each such series being known as a channel. There will be one group of channels for each increment on the distribution of desired speeds.

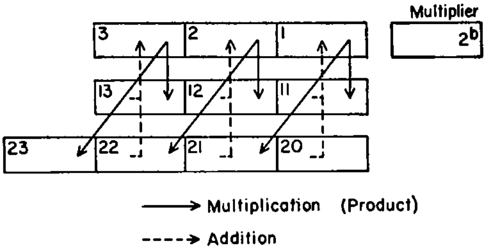

Figure 2. Forward movement of b units is produced by multiplication by 2^b.

TABLE 1
CHANNEL REQUIREMENTS

Number of Lanes	Number of Speed Increments				
	3	4	5	10	16
2	9	16	25	100	256
3		19	31	136	361
4			34	164	452
5				185	530

Each of these groups will contain a sufficient number of channels to represent the actual speeds at which vehicles with a given desired speed may travel. Table 1 indicates the number of channels required for various configurations of lanes and increments on the distribution of desired speeds. From Table 1 it will be clear that if each channel is as long as the roadway, and if the roadway is several memory cells long, a computer of large memory capacity will be required to handle situations having many lanes and/or speed increments.

EXTRACT OPERATION

Before discussing the conflict-checking process it is necessary to understand the computer operation known as extract. Depending upon the design of the particular computer there are variations of extract but the results of one form are derivable from the results of another. In the extract operation, as used here, selected digits of a particular number (called the extractee) are to be lifted out and placed in a memory cell by themselves, thereby forming a new number in which the extracted digits will retain their true value (1 or 0) but all other digits will be "0." To accomplish this, a masking number is used. This masking number has "0's" in the digit positions where extraction is to take place and "1's" in all other positions. The extract operation may then be thought of as allowing the

1 1 0 1 0 1 1 0 1 0	Extractee
1 1 1 0 0 0 0 1 1 1	Mask
0 0 0 1 0 1 1 0 0 0	RESULT

Figure 3. The extract operation.

digits of the extractee to be brought against the mask; where an oppening (a "0") appears in the mask, the digit of the extractee may pass through, but where a "1" appears in the mask, the extractee digit may not pass through. This is illustrated in Figure 3. If desired, a left or right shift may be applied to the extracted result.

To check whether cars in any channel will during the next time interval come too close to any car in another channel, the cars in the faster channel may be copied into a dummy channel in such a way that they are shifted forward by the amount equal to the distance they would travel during the next time interval plus the minimum safe following distance. Then, using the extract operation, the contents of the slower channel may be compared with the contents of the faster channel (shifted forward) to determine if conflicts exist. Where such conflicts do exist they are handled in accordance with the passing or slowing down requirements of the model.

The process of changing speed or changing lane is simply the process of transferring a car from one channel to another. This may be accomplished by subtracting a group of appropriately situated binary "1's" from the source channel and adding this same group to the destination channel.

FIGURE OF MERIT

The purpose of any simulation is normally the optimization of measurement of flow conditions. If measurement or optimization is to take place, there must be some criterion or figure of merit involved. Typical figures of merit might be:

1. Average time for a vehicle to traverse the system.
2. Percent of vehicles which are required to travel at speeds less than their desired speeds.
3. Average number of seconds delay per car mile.
4. Number of lane changes per second.
5. Time lost by cars which are required to travel at less than their desired speeds.

With physical representation, the average time for a vehicle to traverse the system may be computed only with extreme difficulty. In the pilot study to be described later in this paper, a modification of the fifth figure of merit was used to measure the effectiveness.

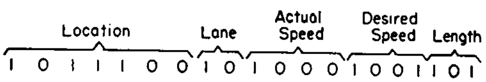

Figure 4. Example of assignment of digits for mathematical representation.

MATHEMATICAL REPRESENTATION

With mathematical representation a number, or word as it is known in computer terminology, is assigned to represent each vehicle. Various groups of digits within the word are assigned to represent various items of information about the vehicle, as shown in Figure 4. Items which can be appropriately included are the location (coordinate) of the vehicle along the roadway, the lane in which the vehicle is travelling, the desired speed of the vehicle, the actual speed of the vehicle, the length of the vehicle, the time at which the vehicle entered the roadway section under observation, and the minimum following distance which the vehicle will maintain behind the vehicle ahead. Manipulations necessary to produce movement through the system, to detect conflicts, to accomplish passing, etc. are all simple arithmetic operations. Forward movement, for instance, is accomplished by adding the actual speed (expressed in distance units per unit time) to the position of the vehicle on the roadway. Lane changing is accomplished simply by changing the digits which represent the lane. Detection of impending encounters may be accomplished by first adding the actual speed of the front vehicle to the position of the front vehicle and subtracting the length of the front vehicle; then, from this result is subtracted the sum of the position of the rear vehicle, the actual speed of the rear vehicle, and the following distance maintained by the rear vehicle; if the result is negative it is unsafe for the rear vehicle to continue in its present lane at its present speed. Since, in this form of representation, the time at which each vehicle enters the system may be easily determined, it becomes relatively easy to compute the time for each vehicle to traverse the system; thus the average journey time becomes a suitable figure of merit. This is not to say that the other figures of merit listed above might not be computed, but the average transit time appears to be a most desirable figure.

PILOT STUDY

A pilot study was made using a system of two lanes and three increments in the distribution of desired speed. The roadway test section was ¼ mile long with an additional 1⁄16 mile at each end as prerun and postrun sections to eliminate end effects. This problem was run on SWAC[2], a computer having a high operating speed but with moderate high speed internal memory storage facilities. Using the technique of physical representation, computing time was between 35 and 38 seconds for each second of real time. It must be remembered, however, that many vehicles were in the system and the computer may be thought of as making all of the decisions being made by all of the drivers in the system at any unit of time.

[2] National Bureau of Standards Western Automatic Computer, now operated by the University of California under support of the Office of Naval Research and Office of Ordnance Research. The work described herein thus received from these agencies valuable support in the form of machine time. This support is gratefully acknowledged.

CONCLUSIONS

While field data were not available with which to make a quantitative comparison, the results obtained were qualitatively consistent with what might be expected. It is believed that the technique of mathematical representation offers considerable promise and a study is under way for the purpose of evaluating the potential of this simulation technique.

REFERENCES

1. Mathewson, J. H., Trautman, D. L., and Gerlough, D. L., "Study of Traffic Flow by Simulation," Proceedings, Highway Research Board, Vol. 34, 1955, pp. 522–530.
2. Goode, H. H., Pollmar, C. H., and Wright, J. B., "The Use of a Digital Computer to Model a Signalized Intersection," paper prepared for presentation at the 35th annual meeting of the Highway Research Board, 1956.