APPLICATION OF DIGITAL SIMULATION TECHNIQUES TO HIGHWAY DESIGN PROBLEMS

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Summary

A study of the operating characteristics of the driver-vehicle combination has yielded a general digital simulation model. This simulation model, which can duplicate traffic flow on a 17,000-ft. section of a freeway including two on-ramps and two off-ramps, can be used to economically evaluate alternate design criteria.

The simulated vehicle in the model, following decision rules based on actual traffic behavior, is allowed to maneuver through the section of freeway under study. The effects of changes in traffic volume, traffic velocity, freeway configuration, etc., can then be evaluated by noting changes in the computer output of traverse time, waiting time on ramp, volume-velocity relationship, weaving complexity, etc.

The computer simulation thus creates a duplication of the real situation at a small fraction of the cost of studying the real system. Furthermore, the simulation allows: (1) the evaluation of various freeway configurations without the expense of their construction, and (2) the performance of controlled experiments impossible to perform with the actual traffic.

Introduction

In recent years, because of the growth of the highway building program, traffic engineers have become concerned over the lack of knowledge about the nature of traffic flow. This lack of knowledge has hampered the design engineer in his ability to design an expressway which will move traffic smoothly and efficiently at a minimum cost. All too frequently after a highway has been opened it has been found that traffic problems arise which require extensive redesign and construction.

For example the following questions have still to be answered.

1. What should be the length of an acceleration lane?
2. What is the effect of traffic flow on locating interchange areas at various distances from one another.
3. What is the effect of various speed minimums and maximums on the traffic flow?

Analytical Models

During the past decade a number of descriptive theories concerning vehicular traffic have been put forward. In an attempt to classify these theories Haig7 proposed three types.

The first, an analytical and deterministic model considers the geometrical and physical characteristics of the automobile and the assumed behavior of the driver. When specific values of velocity, acceleration, and vehicle following behavior are postulated, it is possible to describe the motion of a number of cars in one lane. The results, although precise, are limited to a small number of vehicles. Work in this area has been carried out by Pipes;15 Chandler, Horner, and Montroll;11 and Erenman, Montgomery, Potts, and Rothery.9

A second approach has been to consider traffic as a stochastic process and to treat it by the theory of queues. This approach has been utilized by Newell,13,14 Tanner.16 The theory of queues can, however, only be applied when vehicles move at essentially the same speed and when all vehicles enter the system at one point. Reasonable results have been obtained when traffic is actually queued, velocity uniform and the driver has few free decisions.

The third approach describes traffic flow in a continuum. This approach has been utilized by Newell,11,12 Sun-Chow,13 Greenberg,6 and Lighthill and Whitham.10 All three approaches are limited by the fact that it is
assumed that vehicles do not overtake or pass each other.

Simulation Models

It is, however, possible to construct a simulation model for the study of traffic flow which is much more general than the three types mentioned. Simulation has been defined by Harling as "the technique of setting up a stochastic model of a real system which neither oversimplifies the system to the point where the model becomes trivial nor incorporates so many features of the real system that the model becomes untractable or prohibitively clumsy."

Early work in the field of traffic simulation was carried out by Gerlough, Goode, Wong, and others. Gerlough in a pilot study simulated two lanes of a highway system one-fourth of a mile long. In this simulation model the vehicles were allowed to choose their speeds from a three increment distribution of desired speeds. This program run on the SWAC computer required approximately 35 to 38 seconds of computer time to simulate one second of real time.

Goode in his simulation model represented a single intersection of a simple type. Provisions were made for the origination of cars in lanes approaching the intersection, and for a stochastic mechanism for the determination of the direction of travel of any particular car entering the intersection (i.e., right, straight ahead, or left). The measure of effectiveness used was the average delay per car. The ratio of computer time to real time was 3:2.

Although these early models were of rather limited extent, they indicated that simulation procedures could be used to run controlled experiments in order to gain a better understanding of the nature of traffic flow.

The Expressway Interchange Model

In 1958 the Midwest Research Institute, under a grant from the Bureau of Public Roads, started a research program on the simulation of expressway traffic flow. The first phase of this program was devoted to the simulation of an on-ramp area of the expressway. That model simulated a 1,700-ft. section of a three lane expressway including one on-ramp. Based on the experience of this pilot study a more general model was developed. That simulation model is described in this paper.

The Study Area

The portion of the expressway under study is set up in a $4 \times N$ matrix ($N \leq 999$), Fig. 1. The four rows represent: (1) the three through lanes $1, 2$, and $3$, and (2) the ramp, acceleration, and deceleration lane $5$. Each of the $N$ blocks represents a 17-ft. section of freeway, the approximate length of an automobile. For the simulation runs on the computer, any value of ($N \leq 999$) can be utilized. Locations of interchanges are designated as follows:

- $A =$ ramp input location
- $B =$ nose of on-ramp
- $C =$ end of acceleration lane
- $D =$ beginning of deceleration lane
- $E =$ nose of off-ramp
- $F =$ off-ramp output location

The program is very flexible and permits the on- and off-ramps to be located at any point on the section of freeway under investigation.

Input Factors for Simulation Model

In order to obtain a true duplication of actual traffic behavior on the freeway the simulation model should contain all factors which influence traffic behavior. In this model the following factors are considered:

1. The volume of entering and exiting vehicles.
2. The distribution of vehicles to lanes.
3. The velocity distribution of vehicles.
4. The gap acceptance distribution of merging and weaving vehicles.
5. The acceleration of entering vehicles.
6. The deceleration of exiting vehicles.
7. The distribution to lanes of exiting vehicles.

In addition, all vehicles are allowed to shift lanes in order to pass slower moving vehicles in front of them.

Simulation Procedure

Basically, the procedure consists of simulating the arrivals of cars into the section of highway under consideration and then controlling the action of the vehicle by a set of decision processes. During each second of real time each vehicle in the matrix is examined. The
vehicle is allowed to advance, weave, merge, accelerate, decelerate, or exit according to logical rules describing the behavior of actual vehicle-driver combinations. Just prior to examining all vehicles at each second, each of the input locations is evaluated. Inspection starts at vehicles closest to the end of the section of highway under examination and proceeds to vehicles in the input location.

A description of the over-all logic involved in processing a vehicle through the system is given in the flow diagram (Fig. 2). Detailed flow diagrams for the computer can be obtained in Reference No. 3.

The following parameters are used in the flow diagrams:

- \( V = \) total volume in Lanes 1, 2, and 3; vehicles per hour
- \( V_i = \) vehicles per hour in the \( i^{th} \) lane
- \( V_i = V \)
- \( B_n = \) block number of vehicle under inspection
- \( B_n - 1 = \) block number of vehicle in \( i^{th} \) lane preceding vehicle under inspection
- \( iB_n = \) block number of vehicle in \( i^{th} \) lane parallel to or behind vehicle under inspection
- \( v = \) velocity of vehicle under inspection
- \( iV_n = \) velocity of vehicle in \( i^{th} \) lane, parallel to or behind vehicle under inspection
- \( W = \) time gap

Simulation Output

The present model was programmed so that the following information can be obtained about each simulation run:

1. The volume of vehicles traversing the system in each lane.
2. The volume of vehicles entering the freeway through each on-ramp.
3. The volume of vehicles exiting the system at each off-ramp.
4. The number of vehicles which stop on the acceleration lane.
5. The length of the queue on the acceleration lane.
6. The number of vehicles that desire to exit but cannot.
7. The distribution of through-vehicle traverse times.
8. The distribution of ramp vehicle traverse times.
9. The average vehicle velocity in each lane.
10. The number of weaves from:
   a. Lane 1 to 2
   b. Lane 2 to 1
   c. Lane 2 to 3
   d. Lane 3 to 2

Input Data Preparation

Computer Operating Note

To operate the program, an IBM 704 computer is needed which has at least 6,192 words of core storage. One magnetic tape unit is needed (Logical Tape 0), that one being used to produce an output tape for printing on an off-line printer.

On the Computer Console, Sense Switch 4 should be depressed if it is desired to obtain in the problem output a listing of all problem input parameters.

To run the program, assemble the program deck with a series of Control Cards immediately following the deck. The number and type of Control Cards will control the analyses to be run.

There are 13 different Control Cards that can be entered, which insert the necessary setup data describing the system configuration and velocity and weaving distributions. Appropriate Control Cards should immediately follow the program deck. A Problem Card, containing data peculiar to each analysis then follows and, after this Problem Card, change cards for any of the control cards and other Problem Cards may be entered to control the running of a series of traffic problems.

Control Card Format

The 13 Control Cards are divided into four groups. Five cards provide the velocity distribution data for Lanes 1, 2, 3, and the two possible on-ramps. A second group of five cards provide data concerning gap acceptance for weaving operations. A single card specifies the geometry of the model; the length of the through lanes, the ramp entrance and acceleration lane geometry for both on-ramps, and the deceleration lane geometry and ramp exit for both off-ramps.
A fourth group, containing two cards, gives data concerning the exiting decision process; one card for off-ramp No. 1 and the other card for off-ramp No. 2.

The Problem Card contains a test of identification number, the length of time the analysis is to be run, the volume of through traffic and the input volume to each of the two on-ramps.

Detailed description of Control Card format is given in Reference No. 3.

Study of Interchange Configuration

Various types of controlled experiments can be carried out using this simulation model. For example, experiments on the effects on traffic flow of (1) various on-ramp vehicle volumes, (2) various acceleration lane lengths, (3) various velocity distributions, (4) various geometric configurations, and (5) combinations of the above, can be carried out with this model.

Experiments have been carried out on the effect of traffic flow of spacing between an on-ramp and an off-ramp, under varying traffic volumes.

Interchange Configuration

Two interchange configurations (Fig. 3) were examined. Each configuration was 200 blocks or 3,400 ft. long and contained one on- and off-ramp combination. Each acceleration and deceleration lane was 595 ft. long. In Configuration I, exiting vehicles have 2,465 ft. to travel to the nose of the off-ramp while in Configuration II, the distance is 3,230 ft. In Configuration I, the distance between the acceleration and deceleration lane is 340 ft. and 1,370 ft. in Configuration II. All exiting vehicles were designated at block number 199.

Input Data

Volume of traffic: For both configurations, the input to the simulation was for 750 ramp vehicles per hour. For Configuration I experiments with through-lane volumes of 2,000, 3,000, 4,000, 5,000 and 6,000 vehicles per hour were conducted. For Configuration II experiments with through-lane volumes of 1,000, 2,000, 3,000, 4,000, 5,000 and 6,000 were conducted. Two tests were conducted at each volume.

Distribution of volume to lanes: In all experiments carried out, the traffic volumes were assigned to the three lanes according to the following relationships:

\[
P_1 = 0.43593 - 0.22135\alpha + 0.05730\alpha^2 - 0.00046\alpha^3
\]

\[
P_2 = 0.48820 - 0.03136\alpha + 0.00006\alpha^2 + 0.00024\alpha^3
\]

\[
P_3 = 0.07487 + 0.25319\alpha - 0.05736\alpha^2 + 0.00332\alpha^3
\]

where

- \(P_i\) = proportion of total volume in the \(i\)th lane
- \(\alpha\) = total freeway volume in thousands of vehicles per hour

Velocity distributions: Three different velocity distributions were utilized in the simulations. One velocity distribution was used for the on-ramp vehicles, a second for the vehicles in Lane 1 and a third for vehicles in Lane 2 and Lane 3. These velocity distributions are presented in Table I.

<table>
<thead>
<tr>
<th>Vehicle Velocity (blocks/sec)</th>
<th>Cumulative Per Cent</th>
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<tbody>
<tr>
<td></td>
<td>Ramp Lane</td>
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<tr>
<td>------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1.50</td>
<td>0.026</td>
</tr>
<tr>
<td>2.00</td>
<td>0.061</td>
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<tr>
<td>5.50</td>
<td>0.464</td>
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</tbody>
</table>

Gap acceptance distributions: Three different gap acceptance distributions were utilized in the simulation tests. The distributions for merging vehicles (both stopped and moving) are presented in Table II. The gap acceptance data for vehicles weaving between lanes are presented in Table III.
The over-all results of the experiments indicated that there were no significant effects on the traffic flow patterns of the freeway as a result of this change in geometric configuration. A comparison between the through vehicle traverse times for Configurations I and II are shown in Fig. 4. The effect of increased volume on the number of weaves between lanes is shown in Fig. 5. The computer output also indicated that the number of vehicles stopping on the acceleration lane increased with increased volumes of traffic, Fig. 6.

Conclusions and Recommendations

This study has shown that digital simulation can be used to faithfully duplicate actual traffic flow in an on-off-ramp area of a freeway. The output of the simulation, furthermore, gives measures of effectiveness which can be used to evaluate alternate highway designs.

The simulation experiments performed indicate the need for research and experimentation in a wide variety of areas to answer questions such as the following:

1. What is the effect of various vehicle distributions to lanes on the traffic flow?
2. What is the effect on traffic flow of various distances between adjoining on-ramps?
3. What is the effect of various desired velocity distributions on traffic flow?
4. At what volume of traffic do weaving movements between lanes become hazardous?
5. What is the effect on traffic flow of various volumes of commercial vehicles?

The simulation model developed in this study can serve as an efficient tool to answer these and other problems in the continuous quest for means of moving traffic safely and efficiently.

Acknowledgement

The authors would like to acknowledge the valuable work contributed by Mr. L. Findley in programming the computer.


Study Area Matrix for Computer Simulation of an Interchange Area
Flow Diagram of Over-all Computer Logic
The Configuration of the Two Sections of Freeway Being Examined
Cumulative Distribution of Through Vehicle Traverse Times at a Freeway Volume of 2,000 V.P.H.

Lane 1
Volume 2000 V.P.H.

Lane 3
Volume 2000 V.P.H.
The Number of Weaves in 5 min. on a 3,400-ft. Section of Freeway as a Function of Total Through Volume

**Configuration I**

\[ Y = -10.654 + 0.030X \]

**Configuration II**

\[ Y = 8.441 + 0.025X \]
The Relationship Between the Per Cent of Vehicles Stopping on Acceleration Lane (Y) and the Total Through Volume (X)