INTRODUCTION

Rosenblueth and Wiener\(^1\) stated in 1945, “No substantial part of the universe is so simple that it can be grasped and controlled without abstraction. Abstraction consists in replacing the part of the universe under consideration by a model of similar but simpler structure. Models . . . are thus a central necessity of scientific procedure.”

Models can take on many forms ranging from a simple rule of thumb to a complex mathematical representation. At times, it is necessary to perform a digital simulation utilizing a simulation model. This approach may be required for several reasons.

First, the system under consideration may be so complex that it is not possible to model it in terms of a set of mathematical equations for which analytic solutions can be derived which predict system behavior. Most systems that exhibit pronounced non-linear behavior fall into this class.

Second, even though mathematical modeling of the system may be possible, it may not be possible to obtain an analytic solution to the problem, and thus a simulation may be necessary to predict future behavior of the system.

Third, in many cases, it is either physically impossible or economically unfeasible to perform experimental testing and development. For example, design and development of a spacecraft to meet rigorous reliability and performance specifications required a great deal of knowledge regarding human capabilities in a strange environment—knowledge that was not available before the first manned space flights. One way of obtaining the required data was to experiment using human pilots in actual test conditions. Obviously, this method is not acceptable by the standards of safety established in our space program. However, NASA manned spaceflight center performed large numbers of simulated flights to ascertain system effectiveness and
flight effects on human pilots. Thus, by appropriate modeling, digital
computers were used to simulate conditions that could not be phys­
ically observed.

Simulation has become the working tool of science and technology
since World War II and the advent of large-scale analog and digital
computers. It is extensively used as a design tool in weapons and
aerospace industries as a means of predicting the capability of devices,
components, and total systems that exist only on the drafting board.
Only when a satisfactory design is accomplished by simulation is the
expense of pilot production undertaken. Simulation makes possible
trial-and-error manipulation of a symbolic archetype which leads
naturally to an optimum design.

More recently, attempts have been made to use simulation as a
tool to understand, design, and control systems outside of the area of
the physical sciences. Attempts have been made to build simulation
models of economic systems, inventory control systems, queueing sys­
tems, and scheduling systems with an extraordinary degree of success
in many cases. As in the physical sciences, success depends on determi­
ing which facets must be included in the model for completeness and
what details may be omitted for simplicity and usefulness.

This report describes the purpose and potential of simulation in
the area of traffic flow, especially in urban street configurations where
there are high concentrations of cross flow. The references are not an
exhaustive coverage of the traffic field but a representative sample
of the state of the art.

THE PURPOSE OF TRAFFIC FLOW SIMULATION

This section outlines some of the problems of the traffic engineer
and the rationale and development of using simulation as a tool in
helping to solve these problems.

Traffic Control and Traffic Flow Design

The traffic engineer is concerned with transportation problems
that can be put into two categories: control and design.

Traffic control is an operational problem that can be considered,
first, as individual intersection control, and secondly, as interact­ing
control points for a stream of traffic. In the study of a particular
intersection questions arise such as: Is a traffic signal warranted? If
so, should it be pre-timed or vehicle actuated? When should it be
set on flashing operation? What phasing and interval lengths should
be used? When should turns be allowed? What is the effect of the
local speed limit? What is the effect of pedestrian right-of-way? At the
global level of the traffic problem, the interaction between each con-
troller must be considered, primarily in the form of offsets, such that a
smooth stream of traffic flow can be maintained. Offsets depend on
traffic volume and congestion and thus must be set as a compromise
of different time-of-the-day demands or else they must be changed to
respond to actual demands by means of on-line control.

Secondly, traffic flow can be thought of as not only a system con-
trol problem but also a system design problem. The system consists of
the network of streets and all related aspects of street capacity such as
street width, block length, street parking permits, one-way versus two-
way streets, effect of street closings, effect of inter-state throughway
exits and entrances, and the effect of commercial and residential
development. The traffic engineer has limited control over the system
design parameters, but his objective is to make recommendations based
on meaningful data about decisions to be made by other city authorities.
That is, he should be able to predict the effect of street changes and
population shifts on traffic flow.

The Rationale and Development of Modeling and Simulation

When engineers predicting performance are no longer able to
design and build by using trial-and-error methods alone, they are
forced to structure their knowledge of the system in terms of a model.
The model relates the unknown dependent variables of the system
to independent variables which are known and are at least in part un-
der the control of the engineer. The model should include meaning-
ful measures of effectiveness of the system, such as capacity and delay
in the traffic system.

At least three kinds of models have been developed to study traffic
flow. Empirical models result from studies of the effects of input-
output relationships. The *Highway Capacity Manual* describes a
procedure for determining intersection capacity. More recent empirical
models include “Capacity Analysis Techniques for Design of Signalized
Intersections” and “Calibrating a Gravity Model with Data From
Selected Zones.” The gravity model is based on the theory that
the trips produced in any zone will distribute themselves to other
zones in the study area in direct proportion to the trip opportunities
or attractions in the other zones and in inverse proportion to some
function of the spatial separation between the zones. Empirical models
require a great amount of data for calibration. It is often impossible
to gather this data in the quantity or with the precision desired.
Volumes levels cannot be predicted in advance and the precise con-
ditions sought are always changing.
Mathematical models attempt to predict performance at intersections by hypothesizing certain arrival and departure characteristics and carrying through a mathematical analysis. The early examples of mathematical models concentrated on the characteristics of car following such as Gazis' "Mathematical Theory of Automobile Traffic"\textsuperscript{5} 1967, which summarizes the theory to date as well as listing the original source work in the bibliography. In later work, renewal theory, time series, and other methods were used to analyze delay at intersections. Some attempts have been made at optimization of traffic flow. Linear programming is one approach. Traffic Research Corporation,\textsuperscript{6, 7} now Peat, Marwick, Livingston & Co. has developed a procedure for optimizing signal timing in a large network of streets. Mathematical models also have many drawbacks. An analytical solution to the intersection delay problem is only possible under particular assumptions about traffic control and arrival and departure distributions. The intersection problem is too variable for there to be any neat solution.

The model that we are left with is that of simulation. Both analog and digital simulation have been used to simulate an isolated intersection but for more than one intersection some form of digital memory is necessary to keep track of all intersections.

Extensive work has been performed on digital simulation of an intersection. Many simulation models have been constructed as thesis research or by company effort. Traffic Research Corporation\textsuperscript{8} chose five simulations which appeared to be the most promising and tested them for flexibility, simplicity of operation, output, computation speed and cost, and precision and comprehensiveness as well as internal programming structure and components. They concluded that none were completely satisfactory by their criteria.

Recently, Anacomp Inc. has developed simulation of an isolated intersection as part of an in-house study of traffic flow.

In general, different approaches can be used in digital traffic simulation. The program can be stepped along by time increments or event increments. In the first case, a check is made on the state of the system every time increment regardless of any event. Time increments of 0.5 to 2.0 seconds of real time are most typical. Naturally, in the event interval, time is treated as a dependent variable that is increased by the time increment required for an event to occur. The road can be represented according to whether a vehicle is present or absent or instead the vehicle can be accounted for. Another difference is that many components can be modeled deterministically or probabilistically.
THE POTENTIAL OF TRAFFIC FLOW SIMULATION

Naturally, the desired potential of traffic flow simulation is to answer the questions and issues as previously discussed. How this is accomplished at different levels of computer implementation is discussed in the sequel.

Static Utilization of Traffic Flow Simulation

Simulation can be useful in determining several uncertainties in traffic research even in the case that a dynamic controller, such as computerized traffic control is not being installed.

One of the more successful programs is SIGOP or signal optimization. It was developed to determine optimum cycle lengths, phase splits, and offsets in a grid network. Given appropriate data as to traffic volume, vehicle speeds, and network geometry, SIGOP expresses these in terms of delays and stops (i.e., system costs). A mathematical technique is then applied which minimizes an analyst-specified combination of these criteria, delays and stops. SIGOP has been field tested with mixed results, but with significant improvement in some cases.

Other possible uses of the simulation are:

1. The determination of the estimated number of extra stops which result from uncoordinated signal timing.
2. The determination of the effect of street widening, converting to one-way streets, adding turn lanes, and other design changes.
3. The determination of the effect of installing or removing traffic signals, using pre-timed or vehicle actuated signals, and other control changes.

Dynamic Utilization of Traffic Flow Simulation

The pioneering efforts of several cities and companies in the area of computer control of traffic signals are well known, although these efforts actually lag behind the work performed in Europe. Digital simulation is a natural preliminary step in (1) determining the feasibility of computerized traffic control; (2) if it is determined feasible, determining the requirements of the controller, including hardware, such as number of detectors and their location and the software such as the control algorithm.

Two studies of computerized traffic control are of special interest. In a recent Ph.D. thesis, an optimal dynamic control algorithm is developed, and it is tested on a simulation of traffic flow in Lansing, Michigan. In NCHRP Report 29, report is made on a study
of digital computer control of traffic in a small city, namely White Plains, N.Y. Estimates are made on efficiency and cost. Both of these studies rely heavily on the traffic simulations which precede the application of digital computer control.

REAL-TIME TRAFFIC SURVEILLANCE

Now let us look at another area of study. A well-known result in optimal control of a dynamic system is that an objective measure of system performance can only be optimized if the state of the system is known. However, in many practical applications of control theory it is not possible to determine all of the variables of the system. The measurements of the state variables that are available are too few in number, and they contain random errors. The system itself is subjected to random disturbances. Therefore, the problem is to estimate the state variables of the system from the few available noisy measurements while the system is being randomly disturbed.

In the case that the dynamics of the system are known and the first- and second-order statistics describing the measurement errors and random disturbances are known, then optimal estimates of the state of the system can be determined based on all previous measurements, as depicted in Fig. 1. The solution is due to Kalman and has revolutionized the treatment of control problems in many areas, especially aerospace applications. The advantages of using Kalman filtering in real-time applications for aircraft and space vehicle guidance and navigation are profound. The earlier methods such as Wiener filtering and linear regression techniques do not have the attributes

![Fig. 1. System and Controller.](image-url)
of real-time computation with a digital computer, which have been shown to be of such value in applications of Kalman filtering.

Recently, I have been investigating using this approach in the traffic surveillance problem. Starting with a rather simple 6 intersection model consisting of 5 main arteries with 17 links (see Fig. 2), a simulation of traffic flow with random disturbances has been performed. By observing volume rates at several links, volume rates on the remaining links are estimated. Although results are preliminary rather than final, successful estimates have been found under these conditions.

![Diagram of surveillance system](image)

Fig. 2. Example of Surveillance System.

The value of an analytic technique to determine traffic flow will be obvious to workers in this field. Usually in theoretical studies the number of vehicle detectors is assumed to be very large; in the NCHRP study of White Plains, N.Y. 464 vehicle detectors were specified for 116 intersections. A more practical case is that of Fort Wayne where initially 60 detectors are to be used for 80 signalized intersections. In Wichita Falls, 64 detectors were used for 80 inter-
sections. Since the cost of each detector and its auxiliary equipment ranges from $500 to $1000 in addition to line rental, a considerable savings can be realized by simulating traffic flow conditions to minimize the number of detectors while utilizing modern estimation techniques to provide the necessary information at intersections that are not equipped with traffic sensors. Equally important, this technique provides the information vitally needed for implementing an effective control algorithm.

APPLICATIONS OF COMPUTER ANALYSIS

Simulation of traffic flow can take on many different forms. I will mention a few examples of these that have been performed for the City of Fort Wayne. The hand counts of data were put on tabulating cards so that a listing could be obtained. From this data, a consistency check was performed that yielded percentage of difference in count at each link. Thus, it was possible to examine the data for inconsistent counts, to throw out these bad counts, and make new counts if deemed necessary. Another program was written to compute the percentage turns at each intersection, which is vital information for computerized traffic control. A fourth program was written to give traffic volume for each artery link, and finally, a fifth program gave the volume per hour per lane for each artery link. All of the programs described above covered morning peak, evening peak and off-peak hours of traffic. These programs are examples of the kinds of analysis that can be performed quickly and efficiently once the decision is made to use computer analysis. Naturally with on-line computer facilities, traffic counts can be taken remotely and the entire process can be computerized.

CONCLUSION

The large and complex traffic systems that exist today are not amenable to trial-and-error control. Digital simulation of traffic flow is virtually essential to traffic control at a near-optimum level. Only from a simulation analysis can analytical decisions be made concerning street development, type of intersection control, and the feasibility of computerized traffic control.

REFERENCES