area, it became economical to provide patrol service 7 days/week, 20 h/day.

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Systematic Development of a Highway Maintenance Simulation Model

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The number of interactions involved in the operation of the common industrial or governmental organization of today makes effective management very difficult, especially when the system is constantly changing. One effective method of examining the various aspects of such a system is by means of simulation. This paper reports research required to perform the initial phase and several follow-up stages in the development of a highway maintenance simulation model. This model is expected to provide management personnel in a state highway maintenance program with the opportunity to consider realistic alternatives and to analyze results of various possible actions before physical changes or irrevocable policy decisions are made. The model uses information such as work activities, labor power, equipment, materials, work-crew alternatives, road network consideration, weather characteristics, and scheduling alternatives. The model should give administrative personnel a means of considering a wide variety of typical highway maintenance dilemmas. Situations that only experience and rule-of-thumb reasoning explained in the past can thus be examined through the eyes of statistical indicators.

The number of interactions required to operate an industrial or governmental organization complicates the job of effective management. This is especially true when the system at hand is constantly changing. Simulation provides an effective tool for considering the various aspects of such a system.

This paper deals primarily with the research needed in order to perform the initial and several follow-up stages in the development of a highway maintenance simulation model.

The simulation model being developed is expected to allow highway maintenance management personnel to consider realistic alternatives and to analyze the results of various possible actions before they make any physical changes or irrevocable policy decisions.

PREVIOUS WORK

In 1967 the office of research and development of the Bureau of Public Roads (BPR) sponsored a study on the application of systems analysis to highway maintenance. The study was conducted by the National Bureau of Standards in two phases. Phase 1 was essentially a broad examination of highway maintenance and the identification of problem areas where systems analysis techniques appeared to offer some promise. At the end of phase 1, it was recognized that, in order to realize the greatest benefit from the project, it would be necessary to channel the remaining study resources into a single problem area; the one selected was the development of a simulation model for highway maintenance.

The phase 2 effort (1), however, was not sufficient to develop a working simulation model to its full potential. The model was designed with extensive detail in certain areas and showed excellent potential in some ways, but the program had one significant shortcoming: The simulation model would not operate (run) to the extent that it was intended. The major error seems to have been including too much detail too soon, given the project's time restrictions.

A number of other studies have been conducted that deal with specific portions of the overall highway maintenance problem, such as weather conditions (2,3), road networks (4), job-scheduling techniques (5), maintenance station locations (6), and roadside mowing operations (7). However, none of these addresses the highway maintenance problem as a whole.

SCOPE AND LEVEL OF DETAIL

The purpose of the simulation model is to aid the users to better understand the response and behavior of the highway maintenance system under different conditions.

For example, suppose that highway maintenance management personnel are considering purchasing some maintenance equipment. Reports show that equipment types 5 and 7 are needed more than the other equipment types. The question then arises of whether management should allocate the money for purchasing equipment type 5 only, or equipment type 7 only, or a combination of both, and, if so, how many.

In such a situation the decision maker's goal is to purchase and use sufficient amounts of each equipment type that the total contribution to the system's performance will be as large as possible. In reality, there is only one sure way to know exactly what contribution the addition of three pieces of equipment type 5 will have on the overall maintenance system. That way is to buy them and observe how the system functions with these additional equipment units over a period of time. But the result may be negative or the improvement slight, which indicates that another course of action might have been better. Simulation allows the user to try alternate approaches and to analyze probabilistic results through the model without the risk of physical involvement.

Another example may help to clarify the concept further. Suppose highway maintenance management personnel would like to have some idea of how the additional maintenance jobs could be worked after various combinations of new equipment were purchased. The model can be run for every logical combination of equipment. By examining the performance output, the user can decide which is the preferred choice. It is important to understand that the simulation model itself is not expected to find the optimum solution for any particular problem, but rather to provide sufficient statistical results that describe the state of the system over a period of time for each of the possible alternative courses of action.

ASPECTS OF THE MODEL

The program was developed with the following three primary goals to ensure the practicality and applicability of the model:

1. The model should be flexible in design to allow the input to define any specific maintenance data values and variations required in considering a highway maintenance situation.
2. The model should contain enough detail for good predictions on the district level but little detail above that amount.
3. The model should be applicable to both districtwide and parishwide maintenance operations.

The simulation development process consists of defining the interrelations between the physical elements and the decision processes that comprise the highway maintenance system. In order to represent a system of the level of complexity of this physical situation, a sizable number of elements and factors must be considered. These include various aspects of the work activities, road network factors, and several other special provisions such as weather, scheduling, and emergencies. A more complete listing of the program's elements is given in the list below.

1. Work activities: type of activity, location in the district or parish, seasonality of the activity, weather conditions, severity of defect, frequency and distribution of the number of occurrences for each type activity, and resource needs;
2. Personnel: personnel types, skills, availability of each type, base locations, and cost by personnel type;
3. Equipment: equipment types, personnel required for each equipment type, base locations, availability of each type, and cost by equipment type;
4. Materials: materials types, base locations, availability of each type, and cost by material type;
5. Work-crew alternatives for each activity (listed by work activity type): number of each personnel type, number of each equipment type, and performance rate of the alternative;
6. Road networks: type of surface, rural or urban, average number of occurrences for each type of work activity, and point-to-point travel considerations; and
7. Other considerations: weather characteristics, scheduling alternatives, emergency activities, performance characteristics, absenteeism, overtime, and contract work.

The final simulation model is expected to be able to appropriately incorporate the details involved with each of these considerations and interrelations into a realistic approximation of the actual system. The process is designed to be direct. That is, the user is required to enter variables via a prescribed input format; he or she is asked to specify certain program controlling parameters and, after the program has been executed, is provided with a varied set of statistical indicators that are an evaluation of the system's actions.

OBJECTS OF THE MODEL

In order to approach the problem properly, the objects of the model must be clearly defined. As a general statement, the overall object of the model is to be able to effectively consider the types of problems commonly encountered by highway maintenance administrators that deal with work crew, equipment, and material decisions. To address this situation more specifically the model must include sufficient input capabilities, sufficient computational breadth and depth, and sufficiently differentiating output to reasonably consider and display a wide variety of highway maintenance administrative dilemmas. These problems are such that no available means can effectively differentiate between alternatives. To better describe the type of problem the simulation is intended to address, a series of examples is given below:

1. Evaluate changes in work crew sizes and what effect the addition of two equipment operators would have.
2. Evaluate quantities and types of equipment, for example, whether it would be better to add two trucks of size A or three trucks of size B.
3. Evaluate work scheduling policies, for example, whether long- or short-duration activities should be chosen first when setting schedules with scarce resources.
4. Evaluate different maintenance strategies, for example, which policy is better in the long run for repairing a road defect.
5. Evaluate alternative material, personnel, and equipment base locations, for example, how much of material A should be kept on hand and where it should be located.

Because the situations are so varied and multiple objects naturally exist, the modeling object becomes one of incorporating into the model the capability of dealing with each of a wide variety of possible situations.

MODELING APPROACH

Although it is a slight overstatement to say that there are two types of computer programs—right ones and wrong ones—in a real sense this is very nearly true. One of the primary pressures on any computer-oriented research is the pressure to get the program running. In fact, the larger the problem the higher the risk and the greater the pressure. These factors are intensified if there is a fixed time constraint such as a contract due date on the research.

This section describes the approach used to handle the level-of-detail versus time-constraint problem encountered in this research.

Steps

The procedure used is essentially a three-step process

Figure 1. Model concept.

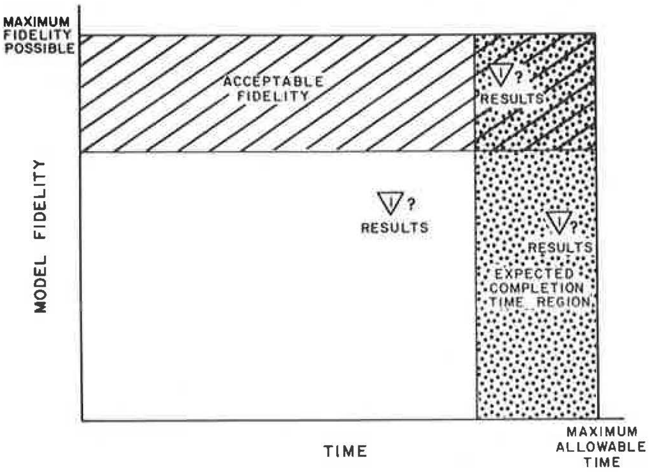
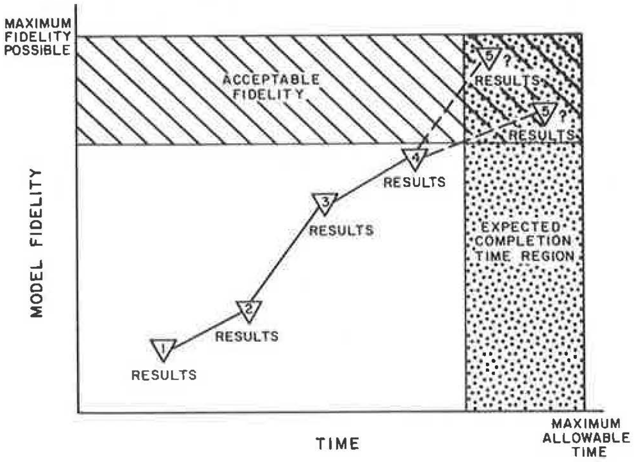


Figure 2. Evolutionary modeling approach.



through which the model evolves into its final form. The steps are

1. Construct an initial, basic (highly abstract, low detail) model;
2. Fully document and preserve the model as a benchmark for future reference and comparative purposes; and
3. Make rapid, distinct, evolutionary changes in the model in order to increase the level of detail (remove abstraction) and improve the fidelity of the model.

These concepts are discussed one at a time in what follows.

Concept

In order to model any system, the physical process must be well defined. However, since it is virtually impossible to completely and accurately describe the process, especially within some limited time constraints, it is sound practice to simplify the model by omitting or assigning constant values to some of the system's variables. The more variables that are suppressed, the higher the degree of model abstraction. As such, a more abstract model would not be expected to represent the real-world situation effectively. The model's fidelity is its ability to reproduce the actual system's results and would likely be rather low. There are some definite advantages to such an approach, however.

First, a working model can be developed in a much shorter time period. Although small problems can often be completed in a relatively brief time, it is very common in the case of larger, more complex problems for the first good run to take several months to achieve (Figure 1). Such a situation is not conducive to positive short-term reporting or to high morale.

Second, the success of the initial venture (Figure 2), without regard to the level of abstraction, is certain to produce a psychological boost to the modeling group and the management personnel group who have supported the project.

There are invariably people within the management decision-making chain who are either opposed to the idea of modeling or skeptical that it can be accomplished. Early reporting of positive results has the effect of attracting the uncommitted management people and strengthening the position of the supportive group. Such results will often produce a change in atmosphere for those who are involved in the project and make data collection and interaction more pleasant and productive.

In the case of the highway maintenance simulation, the final model should reflect all operations, weather conditions, material, equipment, personnel, travel, and the costs associated with the interactions of these units. However, rather than include all these factors from the outset, the initial model was designed to include only five types of operations (rather than the true number of about fifty): good or bad weather conditions, groupings of material and equipment types, a reduction of the various types of equipment operators and work specialists into the single category of "people", and a simplification of the travel calculations. The completion time for such a reduced initial model was much shorter than the completion time for the full model, allowing for the occurrence of the associated benefits discussed previously.

The initial working model thus becomes the first benchmark. Subsequent successful revisions of the model serve to provide higher-level benchmarks, once they have been tested and found to be operating properly. So, rather than make larger significant changes in the model (which may involve a large amount of time), small, rapid, distinct changes are produced. Each of the evolutionary stages represents a working model, complete insofar as the assumptions have described the situation. Each new stage represents a goal, while each new benchmark model represents a goal accomplished.

The approach described is a procedure that has been used effectively throughout the project to protect against the possibility of undesired consequences, such as time limitations and the negative psychological effect of not having any solid indicator of development.

MODEL DESCRIPTION

Assumptions for Initial Benchmark Model

As described previously, the first step in the modeling process was to define a benchmark model with several assumptions and to work on this simplified version of the model before the full scope of details was considered (in single-file order). The assumptions to be made were chosen in such a manner that the sense (i.e., skeleton structure) of the proposed model was not destroyed, but rather so that future development and programming difficulties were reduced. Significant effort was expended in detailing the assumptions so that later extensions would not cause unnecessarily severe difficulties in the programming. These assumptions are given below.

1. There are only five possible work activities instead of the approximately fifty actual work activity types.
2. Differences in the highway types are ignored, although actually there are three types: Interstates, state highways, and farm-to-market roads.
3. Weather is considered to be either good or bad instead of rainy, windy, icy, snowy, foggy, and so forth.
4. There is only one season during the year instead of four.
5. The time increment is considered to be by half days as opposed to hourly, which was also considered.
6. There is only one type of personnel, one type of equipment, and one type of material instead of about six types of personnel, ten types of equipment, and several types of material.
7. Emergency activities occur at the beginning of a period and have a duration of one period, where an emergency activity is an unexpectedly occurring work activity that must be worked immediately.
8. There is only one resource base location, and all the resources in the district (personnel, equipment and materials) are allocated from that point, whereas in reality there may be more than one resource base location.
9. Once a particular crew is assigned to a job, the crew will continue with the assignment until the task is completed.
10. Activities will be assigned to crews on the basis of least cost (for the performance of that activity only).
11. An activity already begun in a previous period has a higher priority in the scheduling process than another activity of the same type that has not yet begun. Also, the highest-priority work activity of all is emergency activity, which has the capability of preempting any ongoing job.
12. The leftover resources for any period fall into two basic categories, productive and nonproductive. They are considered as follows:
    a. In a productive activity a slack-time activity is assumed. There are work activities considered productive that require specific crew sizes and have definite equipment needs but that are "saved" to be worked on when no other productive jobs are able to be performed. In the benchmark model, these jobs are called slack-time activities and are performed when the conditions stated above exist.
    b. In a nonproductive activity a leftover resource is assumed. The final leftover resources that cannot even be assigned to a slack-time activity are referred to as leftovers.
13. The number of occurrences per week for all activities is assumed to be Poisson distributed, and the time between occurrences is assumed to be distributed exponentially.
14. The district or parish is divided into four sections, each of which has a certain distance (represented by a travel time in hours) from the resource location base.

Macroprogram Logic

The initial benchmark model was programmed in two simulation languages, GPSS/360 (8) and GASP IV (9). The macroprogram logic is basically the same in both language versions. Also, because the macrolevel logic does not change later when extensions to the model are made, as additions and modifications are performed, the program flowchart simply takes on more detail, while the direct, initial logic remains virtually unchanged.

After development of working models in both computer simulation languages, the choice was made to perform the remaining modifications by using GASP IV only. This decision was based primarily on the fact that GASP IV, as a FORTRAN-based language, provides a greater degree of programming flexibility and capabilities equal to those of GPSS/360.

In reality, the maintenance work system is initiated by the maintenance supervisor, who drives a truck on the highways of the district spotting defects along the way. As a result, he or she develops a list of work activities that will ideally be worked during the coming week. The simulation model is initiated in a similar manner, by generating the next week's work activity list by using the random number generator and the distributional forms characterizing the occurrences of defects of each type. Space restrictions prohibit a lengthy description of the program itself, but the macrolevel flowchart shown in Figure 3 gives a logical view of the programming approach.

Program Input

The same basic input values are required for both versions of the benchmark model. These include parameters for several probability distributions of work activities, emergency personnel and equipment requirements, defect severity, classification, and weather condition variations. Input is also necessary to specify resource availabilities, various costs, travel times, and activity and crew characteristics. A more detailed input description is given in the list below.

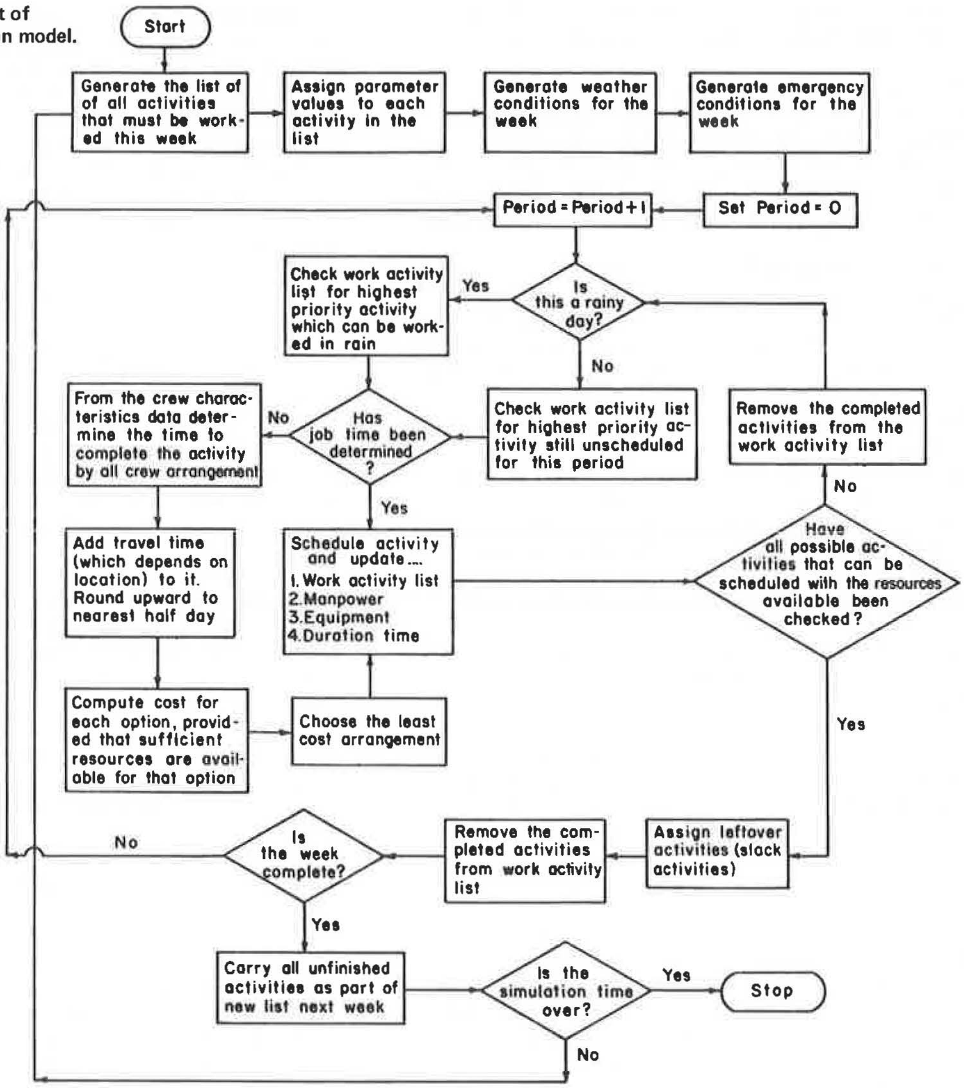
1. Parameters for several probability distributions: occurrence of each work activity (including emergencies), defect severity for each work activity (including emergencies), defect location for each work activity (including emergencies), weather condition parameters, personnel needs for emergency activities, and equipment needs for emergency activities;
2. Resource availabilities at the base location;
3. Cost of various resources per period;
4. Travel times from resource bases to defect locations; and
5. Crew characteristics for each job option: personnel requirements, equipment requirements, and performance rate.

Program Output

The output from the initial benchmark model consists of several statistical indicators that describe the behavior of the maintenance system under the prescribed conditions. The following statistics are collected:

1. Leftover (unused) personnel and equipment levels at the end of each period after slack crews have been assigned, both of which indicate the level of resource use;
2. Proportion of time the preferred crew option is assigned to the job and the proportion of that time the alternate crew was scheduled, given that the preferred crew was not able to be scheduled;
3. Time elapsed from the activity's generation until the activity is begun (i.e., successfully scheduled);
4. For each work activity, the time spent in the system (i.e., time from generation until completion);
5. Time required to accomplish the task once the activity is begun; and
6. The number of crews assigned to the standby (i.e., productive) activity each period, which gives a

Figure 3. Macro-level flowchart of highway maintenance simulation model.



numerical measure of the level of resources not assigned to expected work activities each period but nevertheless used to perform some other productive job.

Each of the statistics plays a unique role in the evaluation of a simulation model.

Example

In order to better understand the role of the model, its input, and its output, a brief example is presented. In fact, the results discussed were taken from the GASP IV version of the benchmark model, but nearly identical values could have been acquired by using the GPSS/360 version. For the sake of brevity, not all input and output values are discussed.

Resource availabilities used as input to the model include 50 personnel units and 28 equipment units. The time between defect occurrences of each type was assumed to be exponential with mean times between occurrences ranging from 5 to 11 periods. The time between occurrences of emergencies was also assumed to be exponential, with an average time between emergencies of 4 periods. Other input was entered and the program executed.

An interpretation of the program's statistical results is presented next. The analysis given is primarily a look at the meaningful statistics collected.

After all activities were considered and the leftover resources were assigned to the slack-time activity crews, on the average about eight units of personnel were left idle (or nonproductively used) every period. Out of the 28 equipment units, approximately 16 on the average were left idle every period. In fact, 8 of the equipment units were never used (minimum leftover units = 8.0). This indicates that the district had more equipment units than were needed. A poor balance apparently exists between the personnel and equipment unit availabilities.

On the average, almost three full crews were assigned to unexpected (but productive) work activities each period. At least at first glance this seems to be a rather large number. In 92 percent of the cases, the activities were scheduled to be worked by their preferred (i.e., least-cost) crew. However, in only 9.2 percent of the cases in which the preferred crew could not be scheduled could the second crew be assigned. Clearly, in the case when the best crew is unable to be assigned, the second preference crew is also normally unable to be assigned.

With the present resource availabilities, many of the activities were started immediately after they were generated. On the average, time from generation to starting work was less than 1 period. However, there were cases in which an activity was started 9 periods after it was generated, indicating that, although it was unusual, some jobs still had to wait. Once the activity was started, 4.74 periods were needed (on the average) to finish it and (on the average) it remained in the system for 5.24 periods after its generation. However, there was a case in which an activity (of low priority, no doubt) took 49 periods to finish.

The decisions to be made by examining these results depend on the highway maintenance management personnel and the realistic options available. However, one possible conclusion is that the district under consideration has more equipment units than necessary.

Also, it should be pointed out that simulation, in order to be effective, often requires numerous executions of the simulation model, that is, numerous examinations under varying parameter conditions. This discussion has been concerned with only a single run, which indicates an incomplete analysis. However, this approach was presented in order to show the type of results generated by the simulation program and to provide a sense of the typical analysis process.

Model Extensions

As described in the section on modeling approach, once the initial benchmark model is operative, extensions that improve the program's fidelity are the next logical step. The following conceptual extensions are considered as one-at-a-time additions to the initial benchmark model.

There may be more than one type of emergency, but emergency activities may last more than one period. Some changes and additions may be made regarding the statistics collected in the benchmark model.

There may be more than one resource location base. This seemingly innocent option adds significant complexity to the model. The reason for this additional complexity lies in the combination aspects of more than one resource base location. Since resources can come from either base location, both the economic and feasible aspects of the problem must be considered.

A standard performance report as output from the model may be included. A system as involved as those included under highway maintenance activities cannot be adequately analyzed with only the basic statistics presented previously. In order to improve the user's understanding of the system, a number of indicators that measure the system's performance were added in the form of a performance report. The report is a slightly modified version of a performance report developed by the Louisiana Department of Transportation and Development.

Expansion of the level of detail regarding personnel, equipment, and material is required. The initial benchmark model considered all personnel to be of one type, all equipment to be of one type, and all necessary materials to be readily available and stored along with the equipment. Of course, this level of simplification is not adequate to describe a realistic system. Later versions of the model include several types of personnel, several equipment unit types, and several material types. In addition, considerations for scheduling activities include an inventory check and an ordering policy.

Additional consideration is needed regarding seasonality for both weather and work activities. The initial benchmark model considers only a single season, with corresponding work activity parameters changed for each of the four seasons and the capability of modifying the work activity parameters as the seasons change. The need for this level of flexibility is obvious when one considers that many activities, such as mowing, are highly seasonal.

Numerous miscellaneous changes in the model will accompany these major modifications. Program units, even those that use the efficient approach of evolutionary change, are rarely ever totally independent. This means that modification occurs throughout the program, even for relatively minor changes in approach. These changes include such items as filing array modifications and variations in the methods of statistical collection. These are not normally thought of as model extensions but have a way of becoming just that.

SUMMARY

The research effort on the highway maintenance simulation model described in this paper is not yet complete. Much remains before the final implementation of the complete system is finished. But the method of development and work plan are readily apparent. This paper deals with the development, the completed steps, the partially completed steps, and the steps to come. The approach is very direct.

After the conceptual model design was completed and what information was expected from the final model was determined, a series of simplifying assumptions were made in order that a first-level, benchmark model could be defined. The simulation of the simplified situation was set as the next project goal. In fact, because the most appropriate simulation language was initially a question mark, the first-level model was programmed in two languages, GPSS/360 and GASP IV. Later, after thorough consideration, GASP IV was chosen as the language to be used in subsequent evolutionary stages.

While progress was being made in programming and debugging the initial model, plans were made regarding expansion of the model. Several of these expansion phases have now been completed, while work on others is still being carried on. The final model, scheduled for completion in mid-1979, will include each of the extensions described in this paper and will be used to address questions that could only be speculated about prior to the model's development.

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Countywide Traffic Signal Maintenance Program

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Creation of an effective traffic signal maintenance program requires gathering and analyzing a large amount of data on existing conditions and on the history of maintenance activities. A model has been developed that allows the testing of various maintenance strategies based on historical data from the system being simulated. The computer program, adaptable to almost any computer, does not require user expertise in programming. Its outputs include summary reports, which are an excellent basis for management control and planning. Labor and budget requirements for achieving various levels of accident reduction can be calculated. The model is a valuable tool both for program budgeting and for short- and long-range planning.

Developing an effective traffic signal maintenance program requires gathering and analyzing data on both the existing conditions of the system and its history of various types of maintenance activities. While such data are generally available in files and charts, retrieval and analysis can be time consuming unless the information is processed by digital computer. The benefits that can be gained from even the simplest analysis of signal maintenance data are numerous and can lead to economic savings, higher levels of service, increased productivity, and decreased liability. The law, as it relates to traffic signal maintenance, is that there is a duty to maintain the lights in a traffic control signal and that a failure to do so may lead to liability if it is a proximate cause of an injury. The erosion of sovereign immunity and the gradual increase in financial liabilities to the community have drawn attention to the maintenance of traffic signal systems.

In most areas, maintenance of the traffic signal system is left to one unit of government, be it state, county, or city. The increase in labor, material, and equipment costs in recent years has caused all such units to take a second look at increased productivity and the maintenance of proper levels of service at stable levels of spending. The effect of these spending reviews has been for those in charge of local traffic signal systems to attempt to reevaluate their current procedures in terms of various alternate maintenance strategies. The problem here, however, lies in the facts that sufficient, easily accessible data files are not available and that analysis techniques remain generally at a level too low to allow significant results or information to be gained or a sound engineering evaluation to be made.

To date, several communities have begun the implementation of computerized maintenance reporting systems that lend themselves to the analysis of maintenance-related data and the possible development of model parameters. One survey of the maintenance management of traffic signal equipment and systems (1) concluded that deficiencies in maintenance lead to signal malfunctions or breakdowns that cause delays to the traveling public, increased accident potential, increased fuel consumption, and air pollution. Thus, it is important to have a program that includes routine and preventive maintenance to ensure that problems be kept to a minimum. The lack of the ability to use such data once they are collected can lead to the improper operation of the maintenance program.

BACKGROUND AND SETTING

The Macomb County Road Commission is responsible for 2250 km (1400 miles) of highways in southeastern Michigan (northeastern suburbs of Detroit). The county covers an area of 1253 km^2 (482 $miles^2$) and encompasses 15 cities and 11 townships, all within the metropolitan region of Detroit. The county has a traffic signal system of approximately 500 traffic signal locations. The signals, which are under the jurisdictions of the various cities, the county, and the state highway department, are all maintained by the Macomb County Road Commission.

Traffic signal maintenance performed by the commission consists of the following types:

1. Routine maintenance: work items that must be performed on a regular basis to ensure the continued operation of the equipment;
2. Preventive maintenance: work items that should be performed at scheduled intervals to minimize the probability of failure of the signal equipment;
3. Emergency repairs: work required to restore traffic signal equipment to its original state after a service failure; and