INTRODUCTION

During the past 30 years the profession of traffic engineering has undergone an extremely rapid rate of growth. The transportation system of the modern world must provide for the safe, expedient, economic, and convenient movement of persons and goods. As a result, traffic engineers have been required to solve increasing numbers of complex problems involving the planning, design, and operation of the highway and mass transportation systems.

In the past the traffic engineer has had to resort to personal experience, seasoned judgment, empirical warrants, component analysis, or quite possibly to a "little bit of luck" in order to solve the problems which have challenged him. Rarely did he possess the necessary tools to analyze mathematically all the related factors as an integrated system. Rather, the system nature of transportation problems has been synthesized from the evaluation of individual components.

Vehicular traffic is not only governed externally by the physical laws of nature, but it is further complicated internally by driver behavior. Today the traffic engineer must evolve his solutions from the combined application of the knowledge afforded by both human-behavioral and physical sciences to the man-machine system of highway transportation. This system includes all those related human (driver and pedestrian), vehicle, roadway, traffic, and environmental variables that must be considered together if economic and efficient solutions are to be realized within the limitation of available manpower and natural resources. Modern-day transportation is so complex that the optimum point of operation of many of its systems is no longer within the intuitive comprehension of any individual. Thus, it seems that the analysis of the system defined by any problem would afford a logical approach for the traffic engineer to follow. This theme constitutes the purpose of this paper.
SYSTEMS ANALYSIS TECHNIQUE

Mr. Webster has defined four of the words in the title of this paper as follows:

1. System—an assemblage of objects united by some form of regular interaction or interdependence,
2. Analysis—the investigation of problems by mathematical methods,
3. Traffic—the flow of pedestrians and vehicles along a street or highway, and
4. Engineering—an applied science concerned with utilizing natural resources for supplying human needs, one of which is transportation.

It is obvious that systems analysis is concerned with the mathematical evaluation of a system made up of related components to develop an optimum solution involving the operations of a system. Traffic engineering, by similar deduction, comprises an applied science with the expressed purpose of optimizing the movement of people and vehicles within the resource limitations. Thus, it may be inferred that systems analysis is indeed a tool for the traffic engineer.

Systems analysis had its start during the Second World War, when many logistic and production problems had to be solved under conditions that taxed the available resources to their limits. Industrial engineers and economists are largely responsible for the development of systems analysis as we know it today. However, signs of worthwhile endeavors are now appearing in the highway and traffic engineering literature.

The three elements of the systems analysis technique are illustrated in Fig. 1. First, a particular problem must be developed into a concept. This conceptual analysis involves defining and delimiting the nature and scope of the problem to be investigated. As an example, a city traffic engineer might be concerned with the optimum location of parking lots in the downtown area. He may want to select these locations so that the total walking time from the lots to the desired destinations is minimized for the drivers coming into the central business district. This engineer also realizes that many factors, such as limited capital and operating funds, parking-space requirements, available land, and traffic flow and distribution patterns, limit his scope of activity. Thus, the first step is to describe the problem in qualitative terms.

After the concept has been fully described, its elements must be formulated into a mathematical model. This model must behave in a way similar to the system being studied. Expressions are developed to describe the conceptual model in quantitative terms. Each mathematical model consists of an objective function and a set of constraints. The
objective function mathematically represents the purpose or goal that the system is to achieve. The constraining equations define the framework within which the system may realistically operate. In the above example, the objective function to be optimized is the expression for total walking time. The optimum solution to this particular problem

SYSTEM ANALYSIS TECHNIQUE

1. Development of concept
2. Formulation of mathematical model
   a. Objective function
   b. Constraints
3. Solution of problem

Fig. 1.

must lie within the constraints imposed by capital and land limitations, parking demands, and prevailing traffic requirements. The second step of the systems analysis technique is to formulate a mathematical model in terms of an objective function that is to be optimized subject to a specified set of constraining expressions.

Finally, the solution to the mathematical model must be obtained. The form of the mathematical model usually suggests a solution to the problem. Several systems analysis approaches available to the traffic engineer are mathematical statistics, linear programming, queueing theory, dynamic programming, simulation methods, inventory and production control models, game theory, and cybernetics. The end product of the systems analysis technique is the numerical solution indicating the optimal operation of the system being analyzed.

TRAFFIC ENGINEERING EXAMPLES

The following two examples have been prepared in the area of traffic operations to illustrate the application of systems analysis to the solution of traffic engineering problems. A complete evaluation of a problem in striping highways or streets is presented as the first case. The other illustration is concerned only with the fabrication of a mathematical model representing the procurement of warranted traffic signs.

Pavement Marking Model

Three marking materials are available for striping the highway pavements in a given area. The costs of these materials, cold paint, hot paint, and plastic markers, are described in Fig. 2. Service ratings were developed from field and laboratory tests. These values represent the combined influence of such factors as visibility, resistance to weathering and wear, and reflectorization. The data for the traffic marking
operation are summarized in Fig. 3 for the three striping materials available. Based on the annual cost concept, the cold paint with a minimum cost of $170 per mile would be selected as the material to be utilized in the striping operation. However, in this case no consideration is given to material performance as indicated by the service ratings.

The conceptual model is stated as:

1. The performance of the striping operation is to be optimized by maximizing the combined service rating of the pavement marking materials used,

![Table: Pavement Marking Materials](image)

![Table: Pavement Marking Operation](image)

2. All paved highways or streets in the area are to be marked, and

3. Activities are limited by the allocated fiscal and manpower resources.

This concept is translated into the mathematical model depicted in Fig. 4. The objective function and the constraining equations have been given real-world meaning by the service ratings and technological coefficients obtained from cost accounting and marking operation records. The limiting values of $185 per mile per year and 3.40 man-hours per mile per year represent, respectively, the annual cost and manpower resources available for the pavement marking operation. The form of this model is a linear programming problem, and the solution is readily obtained by the Simplex algorithm. The optimum answer is to stripe 40.2 per cent of the highways or streets with cold paint, 31.8 per cent with hot paint, and 28.0 per cent with plastic markers. Thus, the performance of the traffic markings has been optimized within the financial and manpower resources at the disposal of the traffic engineer.
There is no better solution to this particular pavement marking operation.

**Traffic Sign Model**

In the traffic sign example it is again desired to maximize the performance of these traffic control devices. Service ratings obtained from field and laboratory tests can incorporate such important factors as legibility, resistance to weathering and vandalism, night visibility, and routine maintenance requirements. The goal of this traffic sign problem

**PAVEMENT MARKING MODEL**

**Objective function:**

Max. \( P = 1.00X_1 + 1.50X_2 + 3.00X_3 \)

where \( P \) = service rating.

- \( X_1 \) = per cent of highway mileage to be striped with cold paint.
- \( X_2 \) = per cent of highway mileage to be striped with hot paint.
- \( X_3 \) = per cent of highway mileage to be striped with plastic markers.

**Constraints:**

1. Mileage; \( X_1 + X_2 + X_3 = 100 \) per cent of the highway mileage to be striped.
2. Annual cost; \( 1.70X_1 + 1.82X_2 + 2.10X_3 \leq \$185.00 \) per mile per year.
3. Manpower; \( 0.030X_1 + 0.025X_2 + 0.050X_3 \leq 3.40 \) man-hours per mile per year.
4. Negative answers are not permissible.

**Solution:**

- \( X_1 = 40.2 \) per cent
- \( X_2 = 31.8 \) per cent
- \( X_3 = 28.0 \) per cent

**Fig. 4.**

is represented in general mathematical notation by the objective function in Fig. 5. The three types of signs considered in this example are reflective sheeting, reflecting spheres, and reflector buttons. It is also assumed that any of these sign types can be purchased or fabricated in the sign shop.

The limit of performance would be infinite unless the traffic engineer is required to stay within certain resource limitations. The budget allocated for traffic signs is a fixed quantity, and the field and shop personnel available for the fabrication, installation, and maintenance of signs is limited. In addition, the traffic engineer is required to provide signs at all warranted locations. These resource limitations are represented by the general constraints in Fig. 5. By obtaining the various service ratings and technological coefficients from laboratory and field studies, cost accounting records, and job assignment reports,
the traffic engineer is able to evaluate this general mathematical model and to determine the optimum procurement of traffic signs for his scope of activity. The answer to this problem provides the most feasible solution.

**TRAFFIC SIGN MODEL**

Objective function:

\[
\text{Max. } P = p_1X_1 + p_2X_2 + p_3X_3 + p_4X_4 + p_5X_5 + p_6X_6
\]

where \( P \) = service rating.

\( p_j \) = individual service rating.

\( X_1 \) = per cent of signs with reflective sheeting to be purchased.

\( X_2 \) = per cent of signs with reflective sheeting to be made in sign shop.

\( X_3 \) = per cent of signs with reflecting spheres to be purchased.

\( X_4 \) = per cent of signs with reflecting spheres to be made in sign shop.

\( X_5 \) = per cent of signs with reflector buttons to be purchased.

\( X_6 \) = per cent of signs with reflector buttons to be made in sign shop.

Constraints:

1. Requirement; \( X_1 + X_2 + X_3 + X_4 + X_5 + X_6 = 100 \) per cent of the warranted signs to be installed or replaced.

2. Annual cost; \( a_{11}X_1 + a_{12}X_2 + a_{13}X_3 + a_{14}X_4 + a_{15}X_5 + a_{16}X_6 \leq b_1 \) dollars per sign per year.

3. Field manpower; \( a_{21}X_1 + a_{22}X_2 + a_{23}X_3 + a_{24}X_4 + a_{25}X_5 + a_{26}X_6 \leq b_2 \) man-hours per sign per year available for field installation and maintenance of signs.

4. Shop manpower; \( a_{31}X_1 + a_{32}X_2 + a_{33}X_3 + a_{34}X_4 + a_{35}X_5 + a_{36}X_6 \leq b_3 \) man-hours per sign per year available for making and refinishing signs in the shop.

5. Negative answers are not permissible.

where \( a_{ij} \) = individual technological coefficient.

\( b_1 \) = resource limitation.

**SUMMARY**

To develop an appreciation for systems analysis, straight-forward examples have been presented. Not all problems encountered by traffic engineers can be so readily stated as mathematical models. The following topics in the various areas of traffic engineering are suggested as possible applications for systems analysis.

1. Planning.
   a. Traffic assignment.
   b. Location and size of parking facilities.
   c. Highway improvement priorities.
2. Design.
   a. Location and size of access points.
   b. Combination of geometric design elements.
   c. Route location.

3. Operations.
   a. Control of freeway operation.
   b. Traffic signal timing.
   c. Allocation of mass transit vehicles.

In conclusion, the following three points should be stressed.

1. Systems analysis is a state of mind. The inquiring engineer is not content with accepting a system as it exists. Rather, he desires to analyze it, find out what makes it operate, determine its response to various stimuli, and cause it to evolve in the best direction. This approach is characteristic of any responsible engineer.

2. Engineers employing systems analysis must often be content with tackling simple problems until confidence in their ability to construct realistic models and produce the correct results from experiments on them has grown in their superiors and colleagues. When this stage is reached, then systems analysis will become a powerful tool in the solution of complex engineering systems.

3. The validity of the answer is only as good as the mathematical representation of the real-world problem.