Analysis and Design of Freeway Incident Response Systems

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Described in this paper is the development of a two-phase procedure for the optimal design of nine specific types of a freeway incident response system. As a basis for analysis, individual system components were classified into three groups according to their functions and design variables: (a) detection, (b) service, and (c) detection and service. Mean response time was selected as the measure of system effectiveness. In the first phase, steps leading toward the optimal disposition of a given number of detection or service units or both in the service area were developed for each component group. The relationship between mean response time and component design variables was first derived. Mathematical programming techniques were then used to determine the optimal component design that minimizes the mean response time. The optimal allocation of a given resource (e.g., annual budget) among competing components of a total system was determined in the second phase by using the results from the first phase. Based on component interactions, the relationship between mean system response time and the response times of individual components was formulated as the objective function of a resource allocation problem. For a given resource, the optimal component integration for a specific type of system was generated by solving this problem. Potential applications of this two-phase procedure in system design and in evaluating alternative system types were demonstrated by numerical examples. Although analysis results and conclusions were limited to the specific types of systems and the hypothetical input data considered in this study, the methodology is general and can be applied to the planning and design of other types of systems not considered here.

On urban freeways carrying heavy traffic, a reduction in roadway capacity due to traffic incidents usually results in traffic congestion. Such congestion not only results in delay to the motorists affected by the incidents but also may cause secondary incidents and delay in treating injured victims. Because of the nature of limited access to nearby service areas from a freeway facility, special problems also arise from the difficulty of summoning aid to the incident site. In view of the adverse effects of traffic incidents, it is evident that there exists the need for a highly responsive and controlled emergency detection and roadside service system to guarantee minimum delay and maximum safety to all motorists.

A traffic incident response system is a multicomponent system for the rapid and adequate response to traffic incident needs. Each component consists of specific hardware and attendant units designed to perform the function of incident detection or service or both. The efficiency of such a system depends not only on the hardware sophistication of its component units but also and, what is more important, on the quantitative mix of different types of component units in the total system and the physical disposition of such units in the service area. A recent review of traffic incident response systems revealed that most of the systems now in operation were developed with limited advance planning and design. Thus, even with current technology, the incident needs conceivably could have been better served if the proper mix of component units and their disposition in the service area had been well reflected in the system design. It is with such a realization that the Institute of Transportation and Traffic Engineering at the University of California, Berkeley, undertook a research study, sponsored by a U.S. Department of Transportation (DOT) university research grant, on the optimal design and operation of freeway detection-service systems (1). Presented in this paper is a particular phase of this research project that gives emphasis to the development and demonstration of an analytical procedure for the optimal allocation of specific hardware and attendant units among various components of an incident response system and their optimal disposition in the service area. This particular phase of research covers four major areas: (a) identification of system components and alternative types of systems selected for detailed study, (b) discussion of system design considerations, (c) analysis and design of system components, and (d) optimal integration of system components in a total system. Many valuable results from previous studies and publications have been used in this study (1, 2, 3, 4, 5, 6, 7, 8, 9, 10).

IDENTIFICATION OF SYSTEM COMPONENTS AND ALTERNATIVES

The study began with a review of the state of the art in traffic incident detection and service techniques and covered the use of ground and aerial patrol units, passing

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motorists, citizens band radios, observers, television cameras, electronic detectors, telephone units, call-box units, stationary police and service units, fire trucks, and ground and aerial medical response units. Among the many types of incident detection and service components, six were selected for detailed study: emergency telephone, call box, police patrol, stationary police, service patrol, and stationary service. Emergency telephone units are those installed on both sides of the roadway at specific intervals to provide direct voice communication between the user and the service dispatcher for the report of incidents and request for needed services. Call-box units are coded roadside radio units for the transmission of incident service requests. The user pushes one or more of the buttons on the unit for the required services and transmits a digitally coded signal to the dispatch center where the signal is decoded and information on calling locations and requested assistance is printed on a tape. Police patrol or service patrol units are specially equipped vehicles moving along the roadway in designated patrol beats. A patrol unit can detect an incident on its patrol route or can be dispatched to the incident site to render required service or evaluate service needs. Stationary police or stationary service units are specially equipped vehicles stationed at strategic locations along the roadway. When an incident occurs, stationary units can be sent by the dispatch center to the incident site to provide needed services or evaluate service needs; these units do not detect incidents.

Within the resource limitations of this study, these six system components were selected for detailed analysis because their effectiveness is particularly sensitive to changes in system design configuration (number of component units and their disposition in the service area); therefore, they are more relevant to the study objective. Although fire fighting and medical response are both important services to traffic incident needs, they were not included in this study mainly because they are part of the overall fire or medical emergency response system for the community. In the analysis and design of these components, consideration should be given to the overall fire and medical service needs of the community, not only to the needs of traffic incidents. Furthermore, past experience has indicated that the frequency of these needs in a traffic incident situation is very low when compared with the frequency of other types of service needs. The inclusion or exclusion of these components in the design of an incident response system will not significantly affect the design of other system components.

Based on logical combinations of the six selected components, nine alternative types of incident response systems were identified by number as shown by the data given in Table 1. In the nine system alternatives considered, the telephone or call box is considered to be the detection component that performs the function of incident detection only. Stationary police and service units are considered to be the service components that render needed services but do not detect incidents. Police and service patrol units can perform the dual function of detection and service and are considered to be the detection and service components. A system alternative can have two different types of components for the same function, such as call boxes together with police or service patrol for incident detection. But different modes of operation of the same type of service are not considered in a system alternative. That is, if the police patrol is used as the detection and service component, stationary police will not be considered in the same system alternative.

SYSTEM DESIGN CONSIDERATIONS

Several external factors influence the optimal design configuration of an incident response system: response process, system objectives, effectiveness measures, incident characteristics, roadway features, and traffic conditions. From the system design point of view, these factors define the conditions for which an incident response system is to be designed and therefore are the input to the design process.

The response process represents the individual activities of various system components in performing their assigned functions and their relationships on the time scale as shown in Figure 1. In general, all of these activities are coordinated at a communication or service dispatch center that receives calls for assistance and dispatches the required service units to the incident scene. The returning of a service unit to its base station was not considered a part of the response process because, with two-way communications, the service unit is available for the next incident as soon as it completes the current service.

Possible objectives of an incident response system were identified and analyzed from the viewpoints of two recipient groups: stranded motorists directly involved in a traffic incident and passing motorists affected by a traffic incident. Based on an analysis of the relationships between alternative objectives, a single objective of rapid detection and service response to an incident was selected as the representative objective for the design of the nine system alternatives considered in this study.

Various forms of system effectiveness measures were considered. Their measurability and reliability were analyzed. Based on the selected system objective, the effectiveness of individual system components and the total system was expressed by the mean response time to an incident. According to Figure 1, the mean response time of a detection component is the mean detection time; that of a service component is the mean service response time; and that of the total system is the mean system response time, which is the sum of mean detection time and mean service response time.

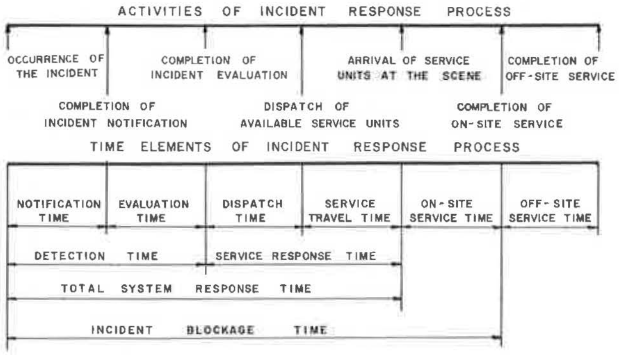
One major input to the design process is the information on when and where traffic incidents occur. Such information usually is generated from the historical incident data for the service area under consideration or can be estimated by using various incident prediction models. Although the generation of incident data was not a subject of this study, a statistical analysis on a set of real-world incident data from the San Francisco-Oakland Bay Bridge was performed to gain a better understanding of traffic incident distribution with respect to time and space and the possible influence of traffic flow conditions and roadway geometric features on such distribution. Within the limits of the uniqueness of the data and its sample size, it was found that, for a 30-min interval, incident distribution can be approximated by the homogeneous Poisson distribution and the influence of both traffic flow condition and geometric feature on incident distribution was significant. Although the bridge incident data may not be typical of freeway incidents, the analysis provided useful insight into the formulation of a basic procedure for the design of incident response systems that is sensitive to the varying conditions of both traffic flow and roadway geometric features.

The frequency distribution of incident service needs was investigated to provide input data for the proper mix of various components in the total system. Four major types of service needs were identified: (a) service (mechanical repair, tire repair, gas, oil, water, and other nonemergency services); (b) police, (c) medical,

Table 1. System alternatives considered.

	Stationary Service Component		Service Patrol Component	
Detection Component	Stationary Police	Police Patrol	Stationary Police	Police Patrol
Telephone	1	2	3	—
Call box	4	5	6	—
Police patrol	—	7	—	9
Service patrol	—	—	8	9

Figure 1. Incident response process.



and (d) fire. Among these four types of needs, service was found to be the most frequently needed.

Major roadway characteristics are the boundary of the service area, the geometric features in the service area such as grades and service routes, the locations of on and off-ramps, and the locations of feasible candidate sites for the disposition of detection and service units. These characteristics not only influence the incident distribution but also determine the feasibility of different types of system components and their operational procedures. In this study, the service area of a response system was defined as the two-way linear section of a freeway. The subsections between consecutive on and off-ramps were considered to be the subservice areas and were treated as the basic design units. However, the actual length of the freeway section and other roadway characteristics can vary depending on the service area under consideration and should be specified by the system designer as input to the design process.

Another important input item is the traffic flow or travel time information for the service area. Traffic flow not only influences the incident distribution but also has significant effect on the delay to passing motorists and the travel time of incident response units. The traffic performance under incident condition is itself an interesting subject to study. Several analytical procedures are available for the calculation of travel time and delay under varying traffic demand and capacity situations such as the FREQ model (2), the flow-dependent travel time function (3), and, under certain assumptions, the tandem queuing model. However, a detailed study on this subject is beyond the scope of this study and empirical travel time data or data from separate analysis by the above methods were assumed to be available as input to the system design process.

ANALYSIS AND DESIGN OF SYSTEM COMPONENTS

Conceptually, the optimal design of an incident response system was approached in two phases. The first phase involved the determination for each selected system component of the optimal design configurations (the optimal disposition of component units in the service area) of given levels of component units. By using the results from the first phase as input, we determined the optimal allocation of a given resource among competing components of a total system in the second phase.

To accomplish the first phase, the design variables of each selected component were first identified. For each selected component, a relationship between the mean component response time (the selected effectiveness measure for the component) and its design variables was developed, and the effect of changes in design variable values on component effectiveness was investigated. For a given level of component units, the optimal design configuration of a component is characterized by the set of design variable values that minimizes the mean component response time. The analysis of individual components was performed for three component groups: (a) detection components, (b) service components, and (c) detection and service components. Each of the six selected basic components of an incident response system was classified into one of these three groups according to its functions in incident response and its design variables. As a basis for the analysis, the service area of each system component is a section of urban freeway of length L, which consists of n subsections (roadway segments between consecutive on and off-ramps); each has length ℓ_i ($i = 1, 2, \ldots, n$). Also all system components were analyzed for a specific time period t during which the incident intensity in each subsection λ_i is considered to be known.

Detection Components

System components of this group consist of discrete communication units (telephones or call boxes) that are installed along the freeway at specific intervals and are connected to the communication or service dispatch center by means of communication links. The design variables of a detection component are the spacings between detection units in different subsections of the freeway facility under consideration. Although the unit spacings in different subsections may not be the same because of varying incident intensities, the unit spacing within a subsection was assumed to be uniform.

The effectiveness of a detection component is measured by the average time required to complete the incident reporting following the occurrence of an incident or the mean notification time as shown in Figure 1. The notification time is the sum of three time elements: recovery time, walking time, and communication time. Recovery time is the time needed by those involved in the incident to react to the situation. It includes the initial examination of the incident situation and self-help by the stranded motorist before he or she decides to use the communication units to call for help. The duration of this time period may vary from less than 1 min to more than 30 min depending on when the stranded motorist decides to call for help. An average of 1.5 min was assumed in the analysis. The walking time is the time required of the stranded motorist to walk from the incident site to the nearest call unit. Because call units are usually installed on both sides of the roadway, the walking distance can be assumed to be the linear distance parallel to the roadway alignment. Based on an assumed walking speed, the mean walking time is a function of the spacing between detection units. The communication time is the time needed to complete the incident report after the call unit is activated. For the call-box unit, the transmission and decoding of the radio signal can be considered instant; therefore, the communication time was assumed to be zero. For the telephone component, however, an average of 1 min was assumed.

Among the three elements of the incident notification time, only the walking time is influenced by the spacing between detection units and the location of the incident. If we assume that the distribution of incident location is also uniform within a subsection, the maximum distance between an incident and the nearest detection unit is one-half of the unit spacing and the average distance is one-fourth of the unit spacing. Based on these considerations and use of the incident intensity in each subsection as the weight, a relationship between the mean notification time of a detection component and its design variables was developed:

$$\bar{t}_n = \bar{t}_x + \bar{t}_z + \sum_{i=1}^{n} (\lambda_i \times s_i) \Big/ \left(\sum_{i=1}^{n} \lambda_i \right) \times 4v \qquad (1)$$

where

$\bar{t}_n$ = mean notification time,
$\bar{t}_x$ = mean recovery time,
$\bar{t}_z$ = mean communication time,
s_i = unit spacing in subsection i, and
v = mean walking speed.

Because both the mean recovery time and the mean communication time are independent of the design configuration of a detection component, the mean notification time varies with the unit spacing in each subsection. For a given total number of detection units in the service area K, the optimal design configuration of a detection component is the unique distribution of K units along the freeway section that yields minimum mean notification time. This unique distribution can be generated by solving the following optimization problem:

$$\text{Minimize } \bar{t}_n = \bar{t}_x + \bar{t}_z + \sum_{i=1}^{n} (\lambda_i \ell_i / k_i) \Big/ \left(\sum_{i=1}^{n} \lambda_i \right) \times 4v \qquad (2)$$

subject to $\sum_{i=1}^{n} k_i = K$ where k_i = number of detection units in subsection i.

An algorithm, DETECT, was developed to solve this optimization problem. By solving the problem for different levels of component units (different values of K), we determined an optimal relationship between level of component units and component effectiveness. Such a relationship was used as an essential input to the optimal allocation of available resources among various components of an incident response system in the second phase of the design process.

Service Components

System components of this group consist of service units (police or service vehicles and their attendants) stationed at strategic locations (base stations) along the freeway section. In an incident situation, service units are dispatched by the communication center to the incident site to provide needed services or to evaluate the incident service needs; but service units do not detect incidents. Two distinctive service dispatch policies were analyzed. The dispatch policy adopted in this study was that the entire service area of the service component is divided into several nonoverlapping service beats (subsections of the freeway section) according to the size of the service area, total number of service units available, and certain desirable constraints on incident service response time. Service units assigned to a particular service beat respond only to the incidents occurring in that beat and always return to the same base station after rendering the needed service.

The design configuration of a service component is characterized by four variables: (a) number of service beats in the service area, (b) size of each service beat, (c) location of the base station for each service beat, and (d) number of service units in each service beat. Under the system objective and selected effectiveness measure, the optimal design of a service component for a given total number of service units is characterized by the best combination of these four variables that yields the minimum mean service response time.

The mathematical relationship between the mean service response time and these four design variables was derived and expressed as the objective function of an optimization problem by treating the service component as an M/G/N queuing system. To find a practical solution to this optimization problem, we investigated the sensitivities of the two elements of the mean service response time (mean travel time and mean dispatch time) to changes in design variable values. The mean travel time was influenced only by the number of service beats, their size, and the locations of their base stations; the mean dispatch time was mostly influenced by the number of service units in each service beat.

Based on these findings, the optimal design of a service component was approached in two steps. The first step is to perform the optimization with respect to the mean travel time under the desirable constraints on the number and size of the service beats in the service area. The output from this step is the best combination of the number of service beats, the size of each service beat, and the location of each base station among a set of candidate sites, which yields the minimum mean travel time for all service units in the service area. After the output from the first step is used as the given condition, the second step is to optimize the distribution of a given total number of service units among individual service beats so that the mean dispatch time of the service component is minimized.

In generating the optimal design of a service component, we also considered several design and operational aspects. First, not every point in or near the service area of the component is economically or practically feasible as a base station for service units. Therefore, the selection of station locations was made from a set of finite and predetermined candidate sites that are considered to be feasible for such a purpose. Second, for economic reasons, it is desirable to minimize the number of base stations for a service area; however, for operational efficiency it is also desirable to have smaller service beats and hence more base stations in the service area. The approach used in this study to compromise cost and operational efficiency is to minimize the number of service beats subject to the constraint that the maximum service travel time in a service beat be below a certain acceptable value. Therefore, the minimum number of service beats in the service area was determined by a predetermined value on the maximum service travel time in each service beat. Finally, the maximum number of service beats is restricted by the smallest of the total number of service units available and the total number of freeway subsections in the service area. All of these considerations were entered into the optimization procedure as constraints.

An algorithm, SERVICE, was developed for the application of the two-step optimization procedure. By repeated application of this algorithm to different levels of total given service units, an optimal relationship between number of service units and minimum mean service response time was developed. Such a relationship served as the basic input to the optimal allocation of resources among competing components of an incident response system.

Detection and Service Components

System components of the detection and service component group consist of police patrol and service patrol units that move along the freeway for incident detection or service or both. The merits of two different patrol strategies (one with overlapping patrol beats and the other with nonoverlapping beats) were analyzed. The patrol strategy with nonoverlapping patrol beats was assumed in this study for the analysis and design of detection and service components.

The incident response time of a detection and service component was analyzed for two cases: (a) when a patrol unit detects an incident on its patrol route and (b) when an incident is detected by some other means and a patrol unit is dispatched to the scene to render required service or evaluate service needs. For both cases, the detection time (the time period from occurrence of an incident to arrival of a patrol unit at the scene) was found to be the most representative and crucial measure of the effectiveness of a detection and service component. Therefore, for a given total number of patrol units in the service area, the design configuration of a detection and service component was analyzed under the objective of minimizing the mean detection time.

The detection time of a patrol unit in a patrol beat is a function of the time headway between patrol units in that beat and is influenced by the following factors:

1. Length of patrol beat,
2. Prevailing traffic condition in the patrol beat for the time period under consideration,
3. Incident intensity in the patrol beat,
4. Number of patrol units assigned to the patrol beat, and
5. Service time of individual incidents served by the patrol units.

Factors 1 and 2 determine the travel time of a patrol unit to complete a patrol loop without interruption for incident detection or service or both. Factors 3 and 4 determine the frequency of interruptions that a patrol unit may encounter during a patrol loop. Factor 5 determines the duration of each such interruption or the delay to a patrol unit due to incident detection or service or both. Based on their influence on mean patrol headway, a mathematical relationship between the mean detection time of a detection and service component and these factors was derived. The optimal design of a detection and service component for a given total number of patrol units was then approached by solving an optimization problem for which this mathematical relationship is the objective function.

For the solution of this optimization problem, an algorithm, PATROL, was developed. For a given number of patrol units in the service area, the algorithm determines the number of patrol beats, the best partition of the service area into such patrol beats, and the best allocation of given units among patrol beats so that the mean detection time of the detection and service component is minimized. A numerical application of the algorithm indicated that both the optimal partition of the service area and the allocation of patrol units among patrol beats vary with the total number of patrol units available in the service area.

OPTIMAL INTEGRATION OF SYSTEM COMPONENTS

The second phase of the system design process involved the optimal integration of individual system components in a total system for a given resource. The optimal integration of system components was treated as a resource allocation problem in which the given resource was allocated, in terms of hardware and attendant units, to individual components of an incident response system. The allocation is such that the resulting mean response time to an incident of the total system is minimized. To accomplish this second phase, the interactions among individual components in a total system and the mean response time of the total system to each of the three different types of incidents were analyzed.

1. Incidents requiring the response of a police unit only,
2. Incidents requiring the response of a service unit only, and
3. Incidents requiring the response of both police and service units.

Based on results from the analysis of component interactions in a total system, a mathematical relationship between the mean system response time and the mean response times of individual components was derived for each of the nine system alternatives considered in this study. By using these relationships as the objective functions and the optimal relationships between component units and the mean response time of individual components developed in the first phase as the return functions, we developed the specific forms of the resource allocation problem for the nine system alternatives. An algorithm, ALLOCATE, was then developed for the solution of these resource allocation problems. With the application of this two-phase procedure, the best design configuration of a specific system alternative for a given resource can be determined in terms of the proper amount of hardware and attendant units assigned to each system component and their best disposition in the service area.

The two-phase procedure is a useful tool not only in system design but also in system planning and evaluation. Its potential applications were demonstrated in several numerical examples. The service area assumed for the numerical examples was an 8-km-long (5-mile-long) urban freeway with five 1.6-km-long (1-mile-long) subsections. Input data on incident intensity, candidate sites for service units, travel times between incidents and service unit bases, distribution of service needs, and the like were either generated from actual observations or assumed for the purpose of illustration. The cost data used were developed from the cost information collected from eight different toll authorities and highway agencies for an earlier study (3). Costs included both capital and operating costs and were expressed annually based on assumed lives of different types of hardware and the pay scale of various service personnel. Because the cost and other input data used in the numerical examples are not typical and were used only to demonstrate the potential applications of the analytical procedure developed in this study, the results and conclusions from such applications, as described below, can only be interpreted within the limits of these data.

To illustrate its use in system design and evaluation, the two-phase procedure was applied to each of the nine system alternatives considered in this study under the constraint of an assumed annual resource of $300 000. As a result of this application, the number of hardware and attendant units assigned to each system component, the mean system response time, and the actual annual cost under the ceiling of the given resource were determined for each system alternative as given in Table 2. Based on Table 2, the merits of the nine alternatives were evaluated by using two different criteria: mean system response time and effectiveness-cost (E/C) ratio. The E/C ratio was defined as the number of minutes saved in mean system response time, when compared to a hypothetical system that has zero annual cost and a mean system response time of 30 min, for every thousand dollars invested annually. The results of this evaluation are given in Table 3. Except for alternative 9, the two criteria resulted in the same ranking of alternatives.

To demonstrate another potential application, the procedure was used to evaluate relative effectiveness of different types of system components for four selected cases.

1. Telephone versus call box,
2. Police patrol versus stationary police,
3. Service patrol versus stationary service, and
4. Police patrol and stationary service versus service patrol and stationary police.

For each case, the mean system response times and the E/C ratios of the system alternatives that have identical other components (alternatives 1 and 4 in the first case) were calculated based on an assumed common number of component units for each system component. The assumed number of detection units for a telephone or a call-box component was 20. The number of vehicles and attendant units assumed for a police patrol or a service patrol component and for a stationary police or a stationary service component was 2. The results of this sensitivity analysis are as follows for case 1, telephone versus call box:

Other Common Components of System	Mean System Response Time (min)		E/C Ratio	
	Telephone	Call Box	Telephone	Call Box
Stationary police + stationary service	8.40	11.11	0.085	0.075
Police patrol + stationary service	7.34	11.54	0.087	0.072
Stationary police + service patrol	7.78	8.61	0.084	0.081

For case 2, police patrol versus stationary police, the results are as follows:

Other Common Components of System	Mean System Response Time (min)		E/C Ratio	
	Police Patrol	Stationary Police	Police Patrol	Stationary Police
Telephone + stationary service	7.34	8.40	0.087	0.085
Call box + stationary service	11.54	11.11	0.072	0.075
Service patrol	7.90	8.61	0.085	0.084

For case 3, service patrol versus stationary service, the results are as follows:

Other Common Components of System	Mean System Response Time (min)		E/C Ratio	
	Service Patrol	Stationary Service	Service Patrol	Stationary Service
Telephone + stationary police	7.78	8.40	0.084	0.085
Call box + stationary police	8.61	11.11	0.081	0.075
Police patrol	7.90	11.54	0.085	0.072

For case 4, police patrol and stationary service versus service patrol and stationary police, the results are as follows:

Other Common Components of System	Mean System Response Time (min)		E/C Ratio	
	Police Patrol and Stationary Service	Service Patrol and Stationary Police	Police Patrol and Stationary Service	Service Patrol and Stationary Police
Telephone	7.34	7.78	0.087	0.084
Call box	11.54	8.61	0.072	0.081
—	11.54	8.61	0.072	0.084

Within the limits of the unique conditions pertaining to the service area and the number of component units assumed for the analysis, four observations were made.

1. The telephone was more effective than the call box as a detection component in all three system alternatives investigated.
2. The police patrol was more effective than the stationary police when the telephone component or service patrol component was present. But police patrol was less effective when the call box was used as the detection component because an on-site evaluation by a police patrol unit was assumed and, for the same number of police units assumed in the analysis, the police patrol had longer mean response time than the stationary police had. When the number of police units in the service area increases, police patrol may become more effective than stationary police for this particular case.
3. Considering the mean system response time, service patrol was more effective than stationary service in all three alternatives investigated. Service patrol was also more effective than stationary service with respect to the E/C ratio in two alternatives. However, with telephone and stationary police as the common components, the two systems had nearly the same E/C ratio.
4. Police patrol plus stationary service was more effective than service patrol plus stationary police when the telephone was used as the detection component. But when the call box was used as the detection component or when there were no discrete detection units in the system, service patrol plus stationary police was more effective.

For the purpose of investigating the effect of different levels of resource on system effectiveness, the two-phase procedure was applied to each of the nine system alternatives at six additional levels of annual resource constraint in $50 000 increments ($350 000, $400 000, $450 000, $500 000, $550 000, and $600 000). For each annual cost constraint investigated, mean system response times for the nine system alternatives were calculated. The relationship between mean system response time and level of cost constraint for each system alternative is shown in Figure 2. Because component units were allocated in integer numbers, the data points in Figure 2 may not match exactly with the assumed levels of cost constraint but rather indicate the actual annual system cost under each cost level. Based on Figure 2, three observations can be made.

1. For all nine system alternatives investigated, mean system response time decreases as cost level increases, but at a decreasing rate.
2. The relative effectiveness of different system alternatives is not uniform at all cost levels investigated. For example, at a cost level below $300 000, alternative 2 has the least mean system response time

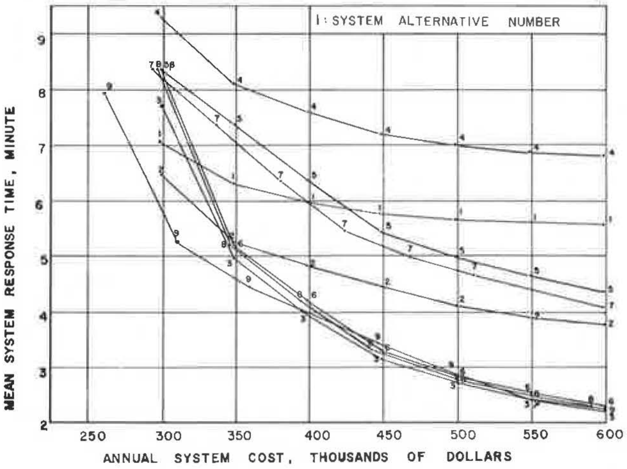
Table 2. Allocation of given resource among system components.

System Alter-native	Number of Hardware and Attendant Units Allocated: Call Box	Tele-phone	Police Patrol	Service Patrol	Sta-tionary Police	Sta-tionary Service	Mean System Response Time (min)	Actual Annual System Cost ($)
1		27			2	3	7.04	299 770
2		15	2			3	6.49	299 650
3		87		2	2		7.69	299 370
4	36				3	2	9.32	299 850
5	15		3			2	8.37	299 600
6	9			2	3		8.37	299 960
7			3			2	8.37	293 000
8				2	3		8.37	296 000
9			2	2			7.90	261 000

Table 3. Comparison of system alternatives.

System Alter-native	Mean System Response Time (min)	Annual Cost ($)	Savings in Mean System Response Time (min)	E/C Ratio	Rank: Based on Response Time	Rank: Based on E/C Ratio
1	7.04	299 770	22.96	0.077	2	3
2	6.49	299 650	23.51	0.079	1	2
3	7.69	299 370	22.31	0.075	3	4
4	9.32	299 850	20.68	0.069	9	9
5	8.37	299 600	21.63	0.072	7	7
6	8.37	299 960	21.63	0.071	8	8
7	8.37	293 000	21.63	0.074	5	5
8	8.37	296 000	21.63	0.073	6	6
9	7.90	261 000	22.10	0.085	4	1

Figure 2. Mean system response time at given levels of annual cost constraint.



of all nine alternatives, but its rank drops to fourth at cost level $350 000. For cost levels beyond $300 000, alternative 3 has the least mean system response time of all nine alternatives. The range of the mean system response times for alternatives 3, 6, 8, and 9 is small, but they are significantly less than those of the other five alternatives considered. This indicates that systems with telephone or service patrol units or both are generally more effective. This may be expected because both telephone and patrol units are more effective detection units and the need for service units is more frequent than for police units.

3. Considering the mean system response time, alternative 4 is the least effective system of all nine alternatives at all cost levels investigated. This indicates that, when call boxes are used as detection units, systems with patrol units are always better than systems with stationary units only.

In addition to these observations, this type of analysis can be very helpful for system planning in two other respects. It provides useful data for the proper selection of system alternatives when an increase in future funding level is anticipated. Also the analysis can be helpful in estimating the required funding level for the desired level of system effectiveness.

SUMMARY

Presented in this paper is a summary description of the development of a two-phase procedure for the analysis and design of freeway incident response systems. The first phase gives emphasis to the analysis of individual system components. For six selected types of components, specific relationships between component effectiveness and their design variables are developed and the effect of changes in component design on component effectiveness is analyzed. The second phase gives emphasis to the analysis of component interactions in a total system. For nine selected system alternatives, the relationships between total system effectiveness and effectiveness of individual components are derived, and steps for the optimal integration of system components in a total system are developed. The usefulness of this procedure in several aspects of system planning, design, and evaluation is illustrated by a set of numerical examples. Although the study results are only applicable to the specific components and system alternatives considered in this study and represent the analytical outcome of a set of assumed input data, the methodology used is general and can be applied to a range of real-world situations or can be expanded to include other types of system components not analyzed in this study.

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