System Challenges of Traffic Incident Management

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Because of the restrictions and limitations confronting efforts to construct new urban freeways, it has become increasingly important to efficiently operate and manage those facilities that exist. Incident management is one element of freeway operation that is under intensive research and that appears to offer significant opportunity for improving the quality and quantity of service provided. This paper defines the various elements of the incident management system. The intent is to identify system considerations that are significant in the design and implementation of an incident management system including within it the elements of cost, response time, performance characteristics, and trade-off analyses.

An incident detection and response system can be separated into three parts: detection, verification, and response. Figure 1 shows these elements along with the cause, the incident occurrence, and the response, the operational recovery.

One of the objectives of any incident management system is to minimize the time between the start of an incident and the completion of a recovery. As a result, the detection, verification, and response elements must be designed to produce a rapid recovery process. The alternatives available to the designer in the definition and specification of each of these elements are described subsequently.

However, for all configurations, the combined delay associated with detection, verification, and response must be considered in the design process. Speedy detection and sluggish response or sluggish detection and speedy response are equally undesirable.

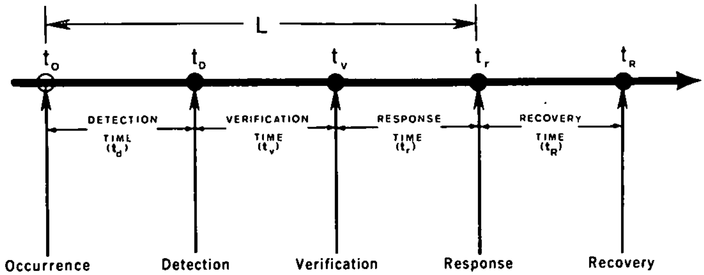
DETECTION ALTERNATIVES

On various U.S. urban freeways a variety of detection alternatives have been used as part of the incident management process (1). In some instances, the detection mechanism contains within it some elements of the verification process as well as elements of the response process. In general, however, detection is an independent function and is accomplished through various mixes of instrumentation, automation, and manpower.

Among the most common detection elements currently used (2, 3) are

1. Motorist call box-telephone systems,
2. Cooperative motorist alarm systems, e.g., FLASH,

Figure 1. Time components of a traffic incident.



3. Patrol-observer systems, e.g., police or rescue,
4. Stationary observer-television surveillance systems, and
5. Electronic surveillance systems.

Motorist Call Systems

One of the first incident detection systems used motorist call boxes (4, 5, 6, 7). With this system, a motorist experiencing an incident proceeds to the nearest call box and informs the operating agency of the nature of the incident being experienced either by selecting a button with a precoded message or by using voice communications or both. The time delay inherent in this type of operation is primarily due to the delay associated with the motorist's determining that an incident has occurred, determining that the proper action involves using the call box, locating the nearest call box, and proceeding to that location to inform the operating agency.

In view of present practices in call box placement, the detection delay in this type of system is often quite significant. In addition, motorist call boxes inherently result in a large percentage of undetected incidents. Many occurrences go unreported because, for example, the incident does not immobilize any one motorist or the motorist attempts to remedy the problem without assistance.

Cooperative Motorist Alarm System

Incident detection that relies on motorist cooperation has been the topic of experimental research for rural freeways and is one of the mechanisms available on toll facilities. One example of this concept is the FLASH system in which passing motorists signal the operating agency by flashing their automobile headlights at an optoelectronic detection system (8).

Another example is verbal communication between motorists and toll collectors at barrier toll stations. In both of these instances, incident reports are received from passing motorists willing to provide cooperation. As a result, a travel time delay from the incident to the monitoring station and the need for multiple reports of a particular occurrence to minimize the false alarm rate contribute to the detection lag time inherent in these systems.

Patrol-Observer System

A variety of patrol-observer systems have been implemented on urban freeways, and in some instances they provide verification and response as well as detection (9). For example, police patrol cars that circulate with the traffic stream provide a commonly used detection mechanism. In these instances, the police patrol detects the incident and verifies the nature and extent of response and the appropriate rescue services. Generally, these vehicles provide little or no assistance for the majority of the incidents requiring aid.

Patrolling service and rescue vehicles provide a similar, but slightly expanded, detection mechanism. In these instances, light-duty service vehicles provide detection, verification, and, in incidents involving minor mechanical failures, response services.

Finally, in high-density traffic on urban freeways, helicopter-borne incident observers have been used for incident detection. Police helicopters are generally used for this purpose and provide both detection and verification.

Stationary Observers and Television Surveillance

Conceptually, the use of stationary observers in strategically located positions is an attractive mechanism for incident detection. However, when two or more observers are required for any given facility, it becomes economically more attractive to use a single observer at a control center and two or more remote-controlled television cameras (10).

Experience with this type of operation indicates that the ability of an observer to detect an incident during a prolonged tour of duty rapidly diminishes. As a result, significant delays are often experienced because the viewer watching the traffic flow does not comprehend that an incident has occurred.

Electronic Surveillance

With the advent of inexpensive, relatively reliable electronic detection equipment and the development of inexpensive digital computer systems, automated surveillance of traffic streams became feasible. With this mechanism, incidents are detected by logically evaluating the variations in flow characteristics (11).

The spacing of detectors along the roadway directly affects incident detection time. Furthermore, because the measured parameters are subject to random variations, data must be averaged in the processing algorithm to ensure that the false alarm rate is acceptably low. Thus, there is an inherent relationship between the delay in the data processing logic and the false alarm rate of such systems.

VERIFICATION

Subsequent to the detection of an incident, the nature and extent of rescue services needed to remedy the problem must be verified. The mechanisms available for this purpose depend on the detection scheme and the competence and reliability of the detection elements. The more commonly used verification processes are

1. Verbal communications by the motorist,
2. Dispatching of land patrol and rescue vehicles,
3. Dispatching of helicopters, and
4. Use of remote-controlled television.

Verbal Verification by the Motorist

As indicated earlier, the verification of an incident and the type of response that is appropriate to remedy the problem are often integrally related to the detection mechanism. For example, in a motorist call box system with voice communications, the dispatcher for the operating agency can interrogate the motorist reporting the incident to determine the character and severity of an incident for which response is requested. Similarly, patrol vehicles provide experienced and knowledgeable evaluators at the scene from whom the dispatcher can determine with reasonable reliability the nature and extent of additional required rescue services.

Vehicle Dispatches

In cases where incident detection does not provide for voice or visual communications, the dispatcher must send an observer to verify incident occurrence and the type of response that is appropriate. For this purpose, two approaches have been used.

The first approach involves dispatching an observer capable of reaching the scene quickly but incapable of providing significant assistance. Typical of this approach is the use of generally available police vehicles, helicopters (12), and the like. The alternative involves dispatching a special-purpose service vehicle that can arrive at the scene reasonably quickly and, in addition, provide the service appropriate for a large proportion of incidents. In this alternative, the verification process is often accomplished by an observer with the capacity to provide remedial assistance for many of the occurrences. In those instances for which additional response is required, the dispatcher is informed and appropriate further action is taken.

Television Surveillance

Under suitable conditions, it is often economically desirable to provide the rescue service dispatcher with the capability of verifying the nature and extent of an incident through the use of remote-controlled television. Using this mechanism, the dispatcher can quickly evaluate the apparent characteristics of the incident to determine the appropriate response. The use of television for this purpose is particularly attractive when electronic surveillance and automatic incident detection are provided, for both approaches use a limited staff at a central control facility.

RESPONSE MECHANISMS

The response capabilities available in an incident management system can generally be separated into three major categories. Class I includes service vehicles capable of providing minimum mechanical assistance, as well as vehicle removal services when the affected automobile remains capable of movement but lacks the power or fuel. When an automobile sustains severe physical damage as a result of collision, overturning, major fire, or even major mechanical failure, generally a tow vehicle capable of clearing the wreckage must be dispatched. These vehicles are aggregated into class II. Futhermore, certain incidents may require the dispatch of selected special-purpose rescue vehicles. Within class III are ambulances, fire fighting apparatus, and sanitation service vehicles.

The particular response methodology used on any specific urban freeway is a design option available to the operating agency. However, the alternatives available for the incident response process somewhat depend on the detection and verification methodologies used. For example, when an incident is verified by a patrol vehicle dispatched to the location at which an incident has been detected, class I rescue services are available. Furthermore, it is frequently considered good practice to provide police patrol vehicles at any location to which class III special-purpose rescue vehicles are sent.

Class I Patrol Vehicles

Patrol vehicles dispatched to incident locations have a wide range of service capabilities. Perhaps most limited of the vehicles in this class are ordinary police cruisers manned by police officers. These vehicles may provide no services other than the initiation of an emergency warning signal to improve highway safety by reducing the probability that additional incidents will result. Furthermore, even the best equipped service patrol vehicle is limited to very minor mechanical repairs. Thus, at best, there is approximately a 28 percent probability that either a class II or class III rescue vehicle will also be required for a typical highway incident.

Class II Tow Vehicles

All incidents in which a vehicle sustains significant mechanical damage and is rendered inoperable require the services of a tow vehicle. Generally, an ordinary tow vehicle can remove passenger vehicles and small trucks. However, there are many incidents in urban areas in which the disabled vehicle is a large truck or bus. In these instances, it is necessary to dispatch heavy-duty tow vehicles with capacity significantly beyond that of ordinary towing trucks.

The primary function of a tow vehicle is to remove a damaged vehicle from the highway. However, as part of this process, it is often necessary to remove wreckage from the areas adjacent to the main roadway or to right a vehicle that has been overturned. In these instances, the towing capacity required may also significantly exceed that of class II vehicles.

The tow truck in class II is restricted to the common size of tow vehicle. Heavy-duty tow trucks suitable for removal of buses, tractor trailers, and the like are generally not available and are included in class III vehicles.

Class III Special Vehicles

Class III vehicles include fire fighting apparatus, ambulances, heavy-duty tow trucks, and sanitation vehicles. These vehicles are generally not required in the more common incidents experienced on an urban freeway. However, estimates based on typical urban freeway characteristics indicate that ambulances and fire fighting vehicles are required approximately 2 percent of the time.

INCIDENT CHARACTERISTICS

To determine the response capabilities that are appropriate for the operation of an incident management system requires that the incident characteristics that are likely to occur be identified. Obviously, incident histories in a particular freeway system will depend on many factors including the geometrics, the nature and characteristics of the users, and volumes and speeds. Although it is not possible to develop a complete characterization that will apply to all freeways, there have been numerous attempts to characterize the relationships between selected identifiable freeway parameters and incident statistics. One typical summary of incident characteristics is given in Table 1 (13). This summary represents a reasonable starting point in the analysis of urban freeway incident problems for use in design of a traffic incident management system.

Analysis of information given in Table 1 reveals that, in approximately 53 percent of the incidents, the problem that occurs is easily solved and the incident is very likely to clear without the aid of external services. Of the remainder, approximately 19 percent involve incidents that require minimal services generally within the capability of the average motorist and certainly well within the capabilities of even the most basic patrol vehicle equipped to provide simple remedial services.

Table 1. Incident characteristics.

Category of Stop	Probability of Occurrence	Vehicle Class Needed
Miscellaneous or nonemergency	0.34	I, II, or III
Tire trouble	0.17	I, II, or III
Mechanical problem	0.17	I, II, or III
Information	0.18	I, II, or III
Gas, oil, and water	0.11	II or III
Medical problem	0.01	III
Fire	0.01	III

Approximately 26 percent of the incidents that occur involve failures that are beyond the repair capabilities of the average motorist but that are easily solved by a trained service mechanic with a reasonably well-equipped service vehicle. The remaining 2 percent involve events and failures that are beyond the repair capabilities of the most advanced technician and mobile vehicle. In these instances, the damaged vehicles must be removed to return the freeway to normal operations.

Within this class of incidents, a wide variety of remedial services are required, including ambulance services, heavy-duty tow trucks, fire fighting apparatus, and sanitation, emergency, and maintenance vehicles.

The types of incidents that require minimal assistance and that are resolved in the shortest periods of time have the highest frequency of occurrence. Similarly, the most severe incidents that require the most significant assistance occur with the lowest frequency. As a result, it is necessary to combine the incident rate with the incident detection, verification, and response time to develop a complete characterization of the traffic incident management problem.

RESPONSE TIME ANALYSIS

A response time analysis can be performed by considering the total detection, verification, and response delay, as well as the time necessary to restore the freeway to normal operations. Alternatively, this analysis can be restricted to the elapsed time between completion of incident verification and initiation of the recovery process during which freeway operations are restored to normal.

Because the total cost to the user is directly related to the elapsed time between the occurrence of an incident and the restoration of normal freeway operations, it is preferable, but more difficult, to consider the former quantity. This quantity can be computed by

$$\hat{T}_e = \sum_{L=1}^{N} P_i(\nu, o)[T_{di}(\nu, o) + T_{vi}(\nu, o) + T_{ri}(\nu, o) + T_{Ri}(\nu, o)] \tag{1}$$

where

$\hat{T}_e$ = expected elapsed time between the occurrence of an incident and the restoration of normal operations,

P_i = probability of a type i incident, and

T_{di}, T_{vi}, T_{ri}, T_{Ri} = detection, verification, response, and recovery times associated with an incident of the ith type.

Furthermore, all of these parameters are functionally dependent on several variables including volume, speed, and average trip length.

As a first-level analysis effort, it is possible to assume a set of constant parameter values and to conduct an evaluation for a prescribed probability distribution of incidents, and a given set of associated delay times. When this is done, it is possible to develop either a statistical description of delay or a single value of the expected user delay. Similarly, it is possible to investigate any reasonable delay quantities on the detection, verification, and response alternatives available to the system designer. In this way, the cause-effect relationship can be developed between the expenditure of funds for specific elements of the traffic incident management system and the net expected delay in the incident response system.

USER COST ANALYSIS

A second and perhaps more meaningful characterization of the effectiveness of a traffic incident management system is the user cost incurred as a result of incidents. One method of evaluating this cost involves computing the expected value of user cost incurred as a result of incidents on the freeway. An analytic expression for this purpose is

$$\widehat{TC} = \sum_{i=1}^{N} P_i C_{Di} \tag{2}$$

where the expected user total cost $\widehat{TC}$ is defined as a function that is dependent on the type of incident i and the delay associated with the occurrence of the ith event.

Furthermore, it is well known that the cost of an ith type of incident directly depends on the time of occurrence. For example, a major collision at the beginning of the rush hour is significantly more costly than the same type of collision at the end of the rush hour. One method of accounting for this direct dependence on the type of occurrence is

$$TC = \alpha \sum_{i=1}^{N} K_i (t - T_i)^2 U_{-1}(t - T_i) \tag{3}$$

where

TC = total cost,
α = cost per unit time,
K_i = function of the changes in capacity-demand,
T_i = time at which capacity-demand changes, and
$U_{-1}(t - T_i)$ = unit step function.

Equation 3 is derived on the assumption that the cost is directly related to the delay experienced by affected motorists. The delay experienced by motorists is quadratically related to the duration of the incident.

A simple analytic model was constructed to identify the costs associated with the occurrence of an incident and the savings available through the proper management control system. In this idealized model, the peak period was characterized by a 2-hour rush period in which the average demand increased from 5,000 to 7,000 vehicles per hour and then dropped back to 5,000 vph (Fig. 2). The actual short-term demand was assumed to vary about the average by ±1,000 vph. The urban highway section under consideration is a four-lane limited-access road designed to the latest standards, and a capacity of 8,000 vph was assumed. Thus, under normal conditions, the peak-hour demand, which varied randomly between 6,000 and 8,000 vph, was assumed to flow along the highway at an acceptable level of service. The occurrence of an incident was modeled as a reduction in the capacity of the highway. The incident was assumed to occur at T_i min after the onset of the rush period and was assumed to persist for a period of L min thereafter as shown in Figure 2. The incident was assumed to reduce the capacity of the highway to 5,000 vph (i.e., one lane was blocked and a gaper effect resulted).

The change in flow, until dissipation, is mathematically described as

$$\Delta f = (D_2 - C_2)\, U_{-1}(t - t_i) - (C_1 - C_2)\, U_{-1}(t - T_i - L) - (D_2 - D_1)\, U_{-1}(T - T_e) \tag{4}$$

where

C_1 = basic roadway capacity,
C_2 = reduced capacity due to an incident,
D_1 = pre-rush-hour demand,
D_2 = peak demand,
L = length of time incident remains on roadway,
T_i = time after onset of rush period that incident began, and
T_e = time after onset of rush period that incident ended.

Subject to these assumptions, the flow onto the section upstream of the incident exceeded the flow past the incident, and upstream congestion was assumed to occur. A queue of unsatisfied demand resulted (Fig. 3). Associated with this queue is a delay cost representing vehicle-minutes of delay experienced in the congested area. The accrual of this is shown graphically in Figure 4.

From the flow equation (Eq. 4) the queue is derived by accounting for the change in flow for each unit of time. Thus, flow Q is described as

$$Q = \int_{-\infty}^{t} \Delta f \, dt \qquad (5)$$

The cost of delay associated with this incident accumulates as the product of the number of vehicles in the upstream queue and the time wasted by these vehicles increase. As a result, the user cost associated with the delayed queue as shown in Figure 4 is directly related to the area under this curve. Hence, the total computation of user delay encompasses the interval from T_i, the occurrence of an incident, through T_e, the time at which freeway operations have completely recovered.

The total cost of delay is given by

$$TC = \int_{-\infty}^{t} \alpha \, Q dt \qquad (6)$$

Thus, for this example the total cost is expressed as

$$TC = \alpha \left[(D_2 - C_2) U_{-3}(t - T_i) - (C_1 - C_2) U_{-3}(t - T_i - L) - (D_2 - D_1) U_{-3}(T - T_e) \right] \qquad (7)$$

As can be seen from the figures, the shape of the queue and total cost curves depend directly on the shape of the demand growth, the capacity curve in Figure 2, and the instant at which the incident is removed. However, generally the queue increases linearly with the duration of the incident, and, therefore, the cost associated with a given incident varies quadratically with the duration of the incident.

Typically, for a 45-min incident, using the above demand characteristics gives an accrued delay of approximately 1,250 vehicle-hours. Based on an average cost figure of \$3.00 to \$4.00 per hour of delay for the vehicles and passengers and the occurrence of 2,000 peak-period incidents per year, the annual cost to the user ranges from \$7.5 to \$10 million. With traffic incident management, it is estimated that response time can be reduced by one-third to one-half.

Given that the accrued cost varies as the square of the response time, these time savings reduce user cost by one-fourth to four-ninths of the amount before an incident management system. This corresponds to an approximate yearly savings of between \$4.1 and \$7.5 million.

As can be seen from this example (14), the nature of the user cost analysis can be investigated with reasonable ease if certain simplifying assumptions are made. Furthermore, a reasonably reliable estimate of the expected user cost can be computed based on logical assumptions regarding the probabilities of incident occurrence.

SUMMARY

A traffic incident management system is an integral part of any urban freeway system. However, in many prior implementation projects, the design of this critically important element has been left to chance and, in many instances, is evaluated as a patchwork solution developed by the operating agency during the final stages of construction or after the highway has been opened. A simple evaluation of incident statistics indicates that urban freeways with ADTs of up to 200,000 vehicles experience as many as 50 in-

Figure 2. Model for characterization of peak-period demand and capacity.

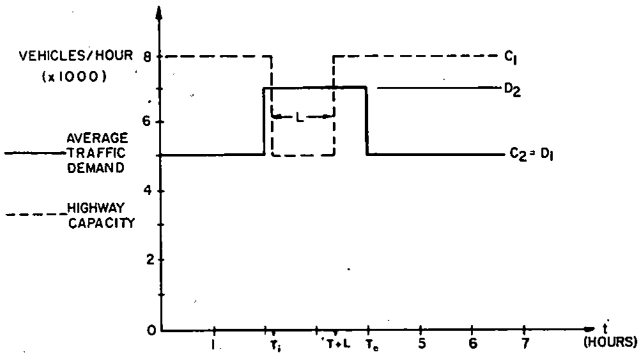


Figure 3. Queue due to unsatisfied demand.

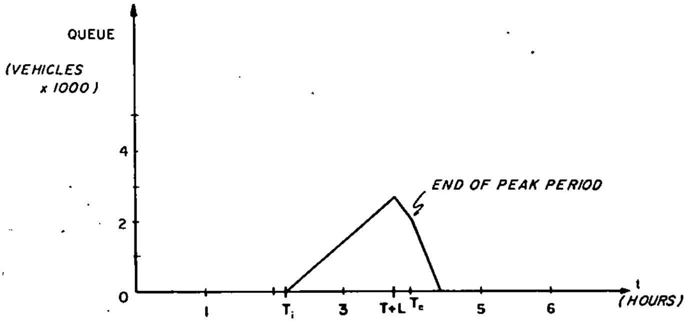
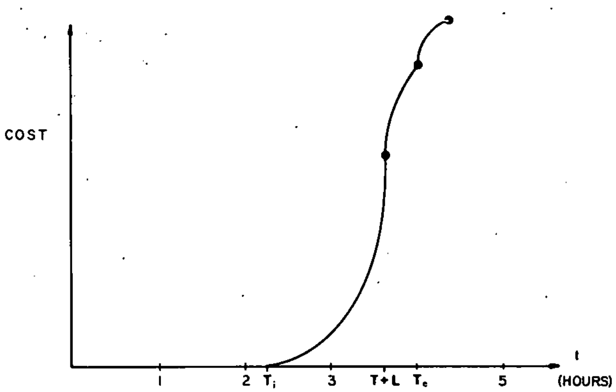


Figure 4. Accrual of cost versus the amount of motorist delay.



cidents per mile per day. Based on this frequency of events, incident management is perhaps the most important single element in maintaining facility production. In view of this, it is extremely important that an incident management system be designed for each urban freeway so as to maximize the benefit-cost ratio for that facility.

There are many challenges to accomplishment of this objective including the following.

1. Analytic procedures must be developed to identify and evaluate the design parameters that affect the performance of an incident management system. Included here are the design relationships that characterize the detection, verification, and response subsystems.
2. Subsystem performance characteristics must be analyzed so as to identify the benefits and disadvantages of the alternative subsystem configurations.
3. Trade-off procedures must be developed to evaluate alternative designs involving man-machine systems for incident management. Consideration must be given to capital and operating costs and equipment reliability, maintainability, and availability throughout the design life of the system.
4. Subsystem components to be used to improve the effectiveness and relieve the burden placed on the operating agency responsible for the freeway facility must be analyzed.

The present situation indicates that the construction of new urban freeways has become extremely difficult, if not impossible. As a result, the emphasis has been shifted to the development of procedures and techniques through which more effective use of available facilities can be achieved. In view of this reemphasis, it is extremely likely that efforts during the next few years will result in the development of sufficiently greater insight into the mechanics of designing and implementing improved traffic incident management systems for urban freeways.

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