ANALYTICAL PROCEDURES FOR ESTIMATING FREEWAY TRAFFIC CONGESTION

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Introduction

A freeway incident--an accident, stalled vehicle, spilled load, or any other event that reduces the normal capacity of the roadway--causes motorist delay. Freeway incident management techniques are directed at reducing this delay, which varies with traffic volume, number of lanes, and the duration of the incident.

The Federal Highway Administration (FHWA) funded research in the late 1970's to develop guidelines and recommendations to help highway departments, police agencies, and other organizations select, plan, design, and implement low-cost measures to deal with incidents that cause freeway congestion. The research results were published in a six-volume report, which presented an overview of the nature and magnitude of the freeway incident management problem and summarized possible solutions. (1) An analytical procedure to estimate traffic delay and congestion and assess the tradeoffs in cost-effectiveness among many alternative measures also was included in the reports. Computational examples and delay, time, and queue tables for typical conditions were provided.

This article summarizes the basic analytical procedures presented in these reports and describes a new, user-friendly microcomputer model for quickly and easily computing delay, time-to-normal flow (TNF), and maximum queue (Q_{max}) caused by freeway incidents.

Representation of Incident Delay

The procedures presented in this article rely heavily on the development of a simple technique for estimating total vehicle-hours of delay. Any freeway incident can cause delay by reducing the number of vehicles that can pass the incident in a given period of time. Even vehicles removed to the freeway's shoulder will reduce capacity as motorists slow to stare at the emergency activities.

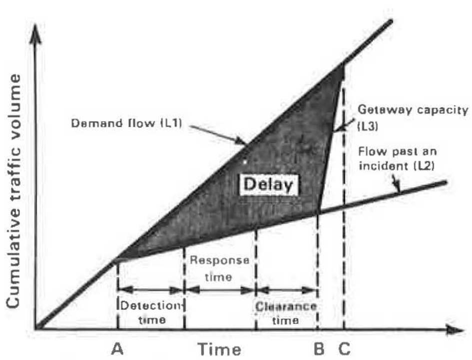


Figure 1. - Quantifying delay caused by a freeway incident.

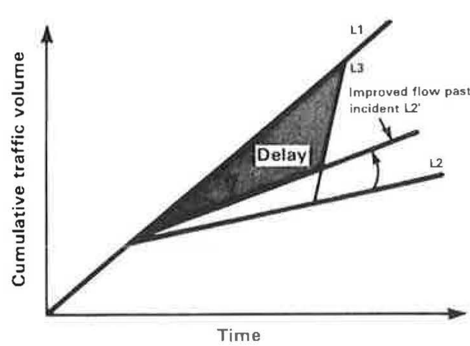


Figure 2. - Delay reduction caused by increasing flow past the incident.

To quantify this delay, traffic volumes and incident durations can be graphically represented, as shown in Figure 1. The horizontal axis is a timeline indicating the occurrence of incident-related events and the overall duration of their impact on traffic flow. The vertical axis is the cumulative traffic volume--the sum of the vehicles passing any given point on the freeway in a defined time period.

The demand flow or volume--the total number of vehicles using the freeway at a given time--is represented by the slope of L1. When an incident occurs (Time A), the reduced roadway capacity (L2) is less than the demand flow because of a lane blockage. This reduced capacity remains in effect until the incident is cleared from the freeway (Time B). At that time, the queued traffic can begin to flow at a "getaway" capacity (L3) approaching the freeway's capacity. When the last vehicle in the queue reaches the normal flow speed and traffic resumes flowing at the demand volume (Time C), the effects of the incident are over.

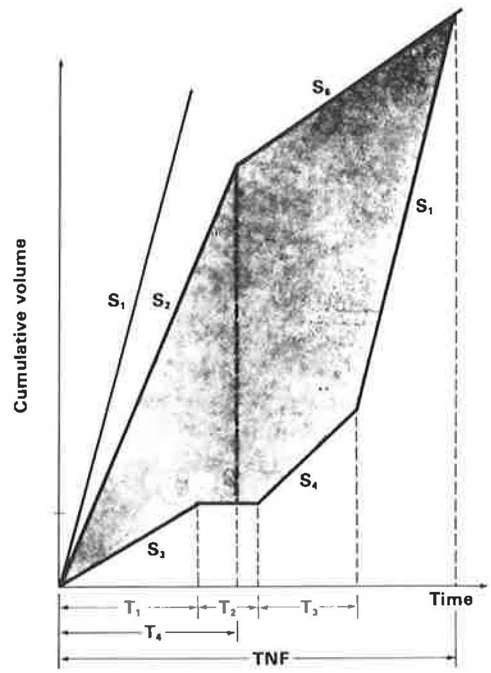
The getaway capacity, or the rate at which vehicles can depart a standing queue, is, in some cases, less than the typical capacity rate (under ideal conditions) of 2,000 passenger cars per hour per lane (pcphpl). Various observations of freeway getaway rates range from as low as 1,500 pcphpl to as high as 2,000 pcphpl. (2-4) Local driving characteristics have a major influence on this range. The analytical procedures described in this article assume the getaway capacity to be equal to the freeway's capacity.

Factors Affecting Incident Duration

A number of factors determine the magnitude of incident-caused delay, which is represented by the shaded area in figure 1. Only some of these factors can be influenced by freeway incident management techniques. Other factors, such as the freeway's capacity and demand flow, generally are fixed by external environmental circumstances such as the number of lanes and time of day. Unless an incident occurs just before or at the end of a peak period or traffic is diverted during an incident, the demand flow rate is assumed to remain constant for the duration of the incident.

Two factors that can be influenced by incident management techniques are the reduced capacity past the incident and the incident's total duration. Effective onsite traffic management techniques optimize use of whatever freeway capacity remains after the incident. Graphically, this is represented in figure 2 by an increase of the slope of the reduced roadway capacity L2 to create an improved flow rate L2'.

Another factor influencing total delay is the time from the moment the incident occurs to the time it is cleared from the freeway. This time interval AB can be expressed as the sum of the detection, response, and clearance times as shown in figure 1. Obviously, minimizing any of these times through efficient incident management will result in less total delay.



S_1 = Capacity flow rate of the freeway, veh/hr.
S_2 = Initial demand flow rate, veh/hr.
S_3 = Initial bottleneck flow rate, veh/hr.
S_4 = Adjusted bottleneck flow rate, veh/hr.
S_5 = Revised demand flow rate, veh/hr.
T_1 = Incident duration until first change, min.
T_2 = Duration of total closure, min.
T_3 = Incident duration under adjusted flow, min.
T_4 = Elapsed time under initial demand, min.
TNF = Total elapsed time until normal flow resumed, min.

Figure 3. — General condition diagram.

Procedures for Estimating Delay

Delay can be estimated for a variety of incident management situations from a general condition diagram (fig. 3). From this diagram, the following equation for computing delay can be derived:

$$\begin{aligned}\text{Total delay} = [&T_1^2(S_1 - S_3)(S_5 - S_3) + T_2^2 S_1 S_5 \\ &+ T_3^2(S_1 - S_4)(S_5 - S_4) \\ &- T_4^2(S_1 - S_2)(S_2 - S_5) \\ &+ 2T_1T_2S_1(S_5 - S_3) \\ &+ 2T_1T_3(S_1 - S_4)(S_5 - S_3) \\ &+ 2T_1T_4(S_1 - S_3)(S_2 - S_5) \\ &+ 2T_2S_5(S_1 - S_4) \\ &+ 2T_2T_4S_1(S_2 - S_5) \\ &+ 2T_3T_4(S_1 - S_4)(S_2 - S_5)]/2(S_1 - S_5).\end{aligned}$$

Similarly, an expression for the TNF can be written as follows:

$$TNF=[T_1(S_1-S_3)+T_2S_1+T_3(S_1-S_4)+T_4(S_2-S_5)]/(S_1-S_5)$$

The general equation to compute the maximum queue, Q_{max}, is somewhat more complicated and is indicated as follows:

$$Q_{max} = T_aS_2 + T_bS_5 - T_cS_3 - T_dS_4 - T_eS_1.$$

T_a, T_b, T_c, T_d, and T_e are functions of the conditions being considered and vary accordingly. However, by definition queue is the algebraic difference between the demand flow L1 and the bottleneck flow L2 at a specific time (figs. 1 and 2). Therefore, Q_{max} can be obtained graphically by computing the maximum difference between L1 and L2.

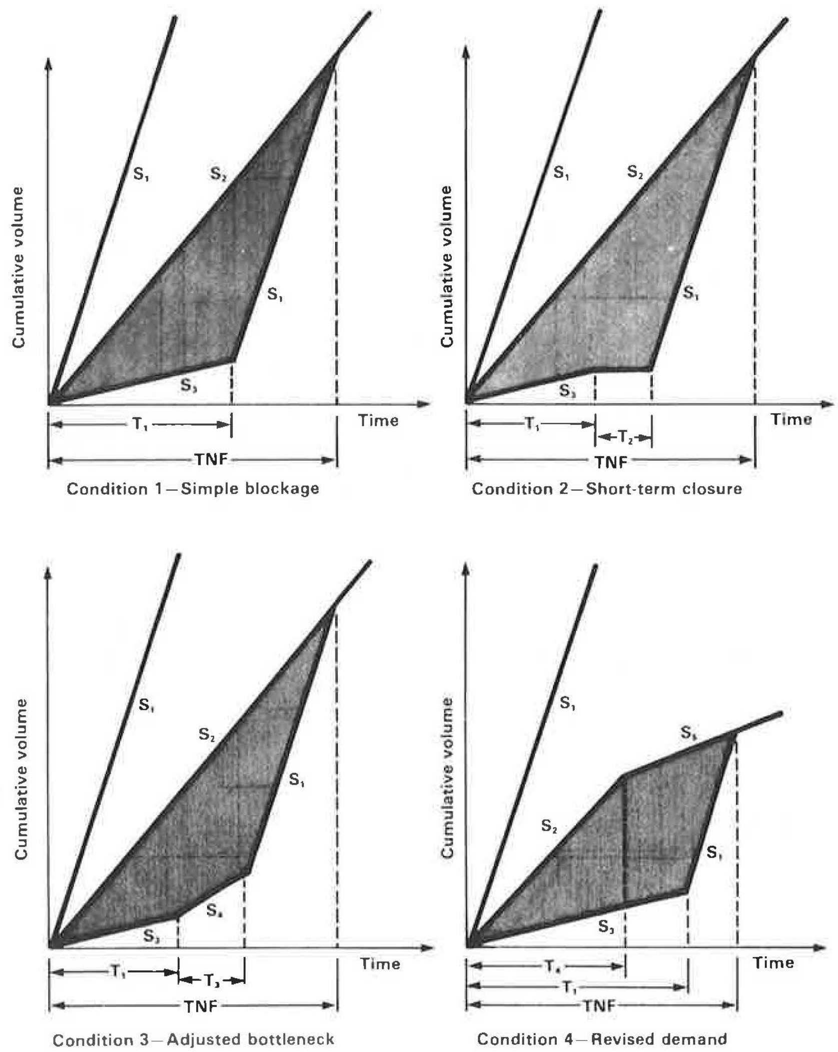


Figure 4. – Delay conditions

It should be noted that these expressions do not apply to every imaginable delay condition and should be used carefully. Four specific delay conditions (fig. 4), obtained from the general diagram (fig. 3) for estimating vehicle-hours of delay, are typical. In these conditions, either the demand flow rate or the reduced flow rate changes because of varying incident circumstances.

In condition 1--simple blockage--the number of vehicles that would have gone through a point if the incident had not occurred (the demand flow) is indicated by S_2. The actual number of vehicles going through this point at the reduced flow rate is shown as S_3. The duration of the incident, from the time of occurrence until the time of clearance, is represented by the time interval T_1. After the incident has been cleared, the queue of vehicles delayed by the incident will move past the point at a getaway capacity S_1 (assumed to be equal to the freeway capacity). Traffic will continue to flow at this rate until all queued vehicles have gone through-at TNF.

The shaded area shown in Condition 1 represents the total vehicle-hours of delay for all the vehicles affected by this incident. Delay will be accumulated whenever the reduced flow rate S_3 is lower than the demand flow rate S_2.

Condition 2 is similar to Condition 1 - but includes a short-term closure on the affected freeway. The time interval T_2 indicates that the freeway is completely closed and that no vehicles can go through the incident point. Vehicle-hours of delay continue to accumulate as more vehicles join the queue forming behind the closure.

Condition 3 is similar to Condition 2 except at the time interval T_1 the bottleneck flow is adjusted, and the onsite flow rate is increased for a period before total clearance by improving the flow of traffic through effective traffic management (such as police officers directing traffic) or by reopening lanes previously blocked by debris and wreckage. The time interval T_3 indicates how long this improved flow rate S_4 is in effect before the getaway capacity S_1 can be attained.

Condition 4 is created when the demand flow rate S_2 is reduced during the incident. This condition typically is caused by natural or artificial upstream traffic diversion or by typical fluctuations in traffic volumes, such as those that occur at the end of a peak period. The demand flow rate drops from S_2 to S_5 at time T_4.

With the appropriate substitutions, these four conditions can, of course, be derived from the general equations. For example, under Condition 1, $T_2=T_3=T_4=0$, $S_4=S_3$, and $S_5=S_2$.

Table 1. - Typical flow rates (veh/hr)

		Bottleneck capacity	
Number of lanes in one direction	Freeway capacity (S_1)	One Lane blocked (S_3)	Shoulder blocked (S_3)
2	3,700	1,300	3,000
3	5,550	2,700	4,600
3	7,400	4,300	6,300

Application of Procedures

Total delay is a function of three variables: Remaining capacity, traffic demand, and incident duration. At least three and up to five flow rates (depending on delay conditions) must be known or estimated to calculate delay. Some of these flow rates can be measured easily in the field for particular freeway sections. Average volumes based on historic data also can be used. Table 1 presents typical capacity flow rates S_1 and bottleneck capacity flow rates S_3 for both in-lane and shoulder incidents for freeways of two, three, and four lanes. (1)

Once the necessary flows and durations are known, total delay, TNF, and Q_{max} are computed by solving the general equations presented previously or by using the interactive spreadsheet. The spreadsheet uses LOTUS 1-2-3 running on an IBM-compatible microcomputer with at least 128k of memory. The program interactively guides the user through a series of screens to enter the required data (flows and incident durations) and computes the total delay, TNF, and Q_{max}. In addition, the delay condition being specified is graphically displayed. The results and graph can be printed as well.

Individual entries can be changed to determine the hypothetical effect of variations in traffic demand and/or incident duration.

Consider the following example:

At 8:15 a.m., a three-lane freeway with a capacity of 5,550 veh/hr carries a demand flow of 4,500 veh/hr. At this time, an accident occurs and a vehicle blocks one lane, which creates a bottleneck flow of 2,700 veh/hr. It takes 25 minutes for the incident management crew to learn of the incident and arrive at the site. While the vehicle is removed, the entire freeway is closed for 5 minutes. Once the vehicle is removed, the bottleneck flow improves to 3,500 veh/hr for 10 minutes before reaching its getaway capacity (5,550 veh/hr). Hourly volumes indicate that a decrease in the demand flow (to 2,800 veh/hr) is expected at 9 a.m.

This example uses all the variables needed to compute delay and TNF as expressed in the general equation:

- S_1--the capacity flow rate of the freeway--is 5,550 veh/hr.

- S_2--the demand flow at the time of the incident--is 4,500 veh/hr.

- S_3--the initial bottleneck flow rate--is 2,700 veh/hr, which remains in effect during the 25 minutes it took the incident management crew to learn of the incident and arrive at the site (T_1).

- S_4--the adjusted bottleneck flow rate--is 3,500 veh/hr, which lasts 10 minutes (T_3).
- S_5--the revised demand--is 2,800 veh/hr, which is expected to occur at 9 a.m., or 45 minutes (T_4) after the incident.

- The entire freeway is closed for 5 minutes (T_2).

Under simpler conditions, some of these variables do not apply and are substituted with zeros.

The data are entered in the microcomputer model, and the results are obtained (fig. 5). The total delay caused by this incident is 803 vehicle-hours, and it would take 71 minutes for the effects of the incident to dissipate.

A METHOD FOR CALCULATING DELAY, TIME AND QUEUE FOR TRADE-OFF ANALYSES

Any Place, U.S.A.

Number of Lanes:		3
Capacity flow rate of the facility, veh/hr............	S1 =	5550
Initial demand flow rate, veh/hr......................	S2 =	4500
Initial bottleneck flow rate, veh/hr..................	S3 =	2700
Adjusted bottleneck flow rate, veh/hour...............	S4 =	3500
Revised demand flow rate, veh/hr......................	S5 =	2800
Incident duration until first change, min.............	T1 =	25
Duration of total closure, min........................	T2 =	5
Incident duration under adjusted flow, min............	T3 =	10
Elapsed time under initial demand, min................	T4 =	45

RESULTS:		
	Total Delay, veh-hrs =	803.4
	Time to Normal Flow (TNF), min =	71.3
	Maximum extent of queue, veh =	1375
	Maximum length of queue, miles =	2.60

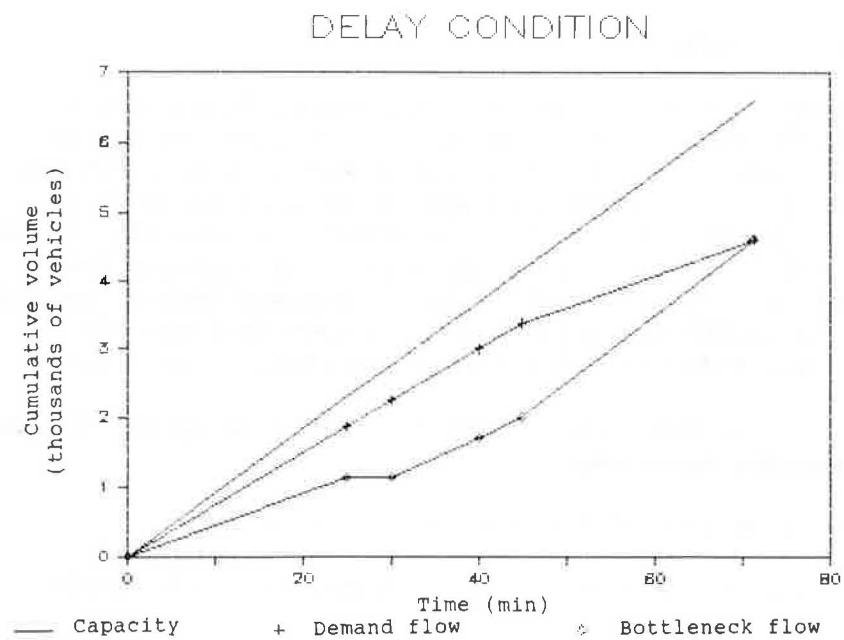


Figure 5. - Sample printout-25 minute detection and arrival time.

If it took only 15 minutes for the incident management crew to learn of the incident and arrive at the site, T_1 would be changed to 15 minutes (fig. 6). Total delay then would be reduced to 572 vehicle-hours, and TNF would be reduced to 61 minutes.

Summary

This article describes analytical procedures to estimate delay, TNF, and the Q_{max} caused by freeway incidents and discusses the availability of an interactive LOTUS 1-2-3- spreadsheet for fast computations. This microcomputer tool easily can be used to estimate the impact of planned incidents (that is, lane closures during construction or maintenance

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Number of Lanes: 3

Capacity flow rate of the facility, veh/hr............S1 =		5550
Initial demand flow rate, veh/hr.......................S2 =		4500
Initial bottleneck flow rate, veh/hr...................S3 =		2700
Adjusted bottleneck flow rate, veh/hour................S4 =		3500
Revised demand flow rate, veh/hr.......................S5 =		2800
Incident duration until first change, min..............T1 =		15
Duration of total closure, min.........................T2 =		5
Incident duration under adjusted flow, min.............T3 =		10
Elapsed time under initial demand, min.................T4 =		45
RESULTS:	Total Delay, veh-hrs =	572.5
	Time to Normal Flow (TNF), min =	60.9
	Maximum extent of queue, veh =	1242
	Maximum length of queue, miles =	2.35

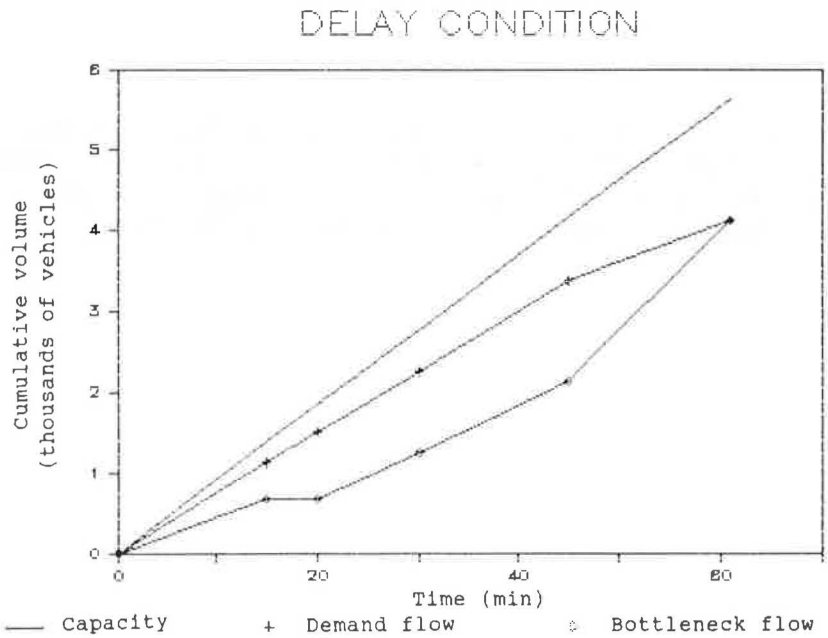

Figure 6. Sample printout--15 minute detection and arrival time.

operations) and the consequences of freeway incidents for immediately determining the optimum traffic control strategy.

This spreadsheet can be obtained, without charge, by mailing an IBM-formatted, 5 1/4-in floppy disk to:

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References

(1) "Alternative Surveillance Concepts and Methods for Freeway Incident Management," Report Nos. FHWA-RD-77-58/63, Federal Highway Administration, Washington, DC, March 1978.

(2) J.A. Lindley and S.C. Tignor, "Getaway Flow Rates for Freeway Incident and Geometric Bottlenecks," Public Roads, vol. 43, No. 1, June 1979, pp. 1-7.

(3) J. Duke, J. Shofer, and A. May, "A Statistical Analysis of Speed-Density Hypotheses," Highway Research Record 154, Transportation Research Board, Washington, DC, 1967.

(4) "Highway Capacity Manual--Special Report 209," Transportation Research Board, Washington, DC, 1985, p. 6-7.

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