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16. ABSTRACT

Headquarters Traffic Department, in cooperation with various Districts, has been conducting a "Statewide Study of Delay to Traffic Due to Lane Closures During Construction Operations" for the purpose of gathering information to be used in estimating delays to traffic during future resurfacing operations. The information presented here was developed through observations of various construction projects involving lane closures. Projects studied included 4, 6, and 8 lane freeways mostly in the larger metropolitan areas.

It was found that the delay encountered in these studies could be grouped into two categories:

1. Where the flow of traffic is below the capacity of the restricted roadway, the traffic will continue to be in a free-flow condition with only minor delay caused by the presence of workers and equipment in the area and reduced speed limits.

2. Where the rate of flow of traffic exceeds the capacity of the restricted section, a queue will form upstream resulting in quite a large delay.

Except in the large metropolitan areas, or other places where flow approaches the capacity of the facility, it is anticipated that most delays encountered will fall into the first category.

Part I of this paper deals with the development of a theoretical way to calculate a delay caused by a queue. The actual delays as calculated for many of the projects were compared with this theoretical method and the results were found to be quite close.

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John Dearson

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Economic Comparison
of Pavement Types

TO: I - Sam Helwer
II - H. S. Miles
III - A. S. Hart
IV - R. A. Hayler
V - R. J. Datel
VI - W. L. Welch
VII - E. T. Telford
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Attached for your information is a copy of Traffic Bulletin No. 7, Delay to Traffic Due to Future Resurfacing Operations. This bulletin has been prepared as a guide for estimating delays due to resurfacing for making economic comparison of pavement types as outlined in Circular Letter No. 63-169, dated June 24, 1963.

We are forwarding additional copies under separate cover to be distributed to key personnel in the District.

J. E. Wilson

J. E. WILSON
Traffic Engineer

Beaton 6/17

Attach.

Separate Cover

Zube

Smith

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

J. E. Wilson, Traffic Engineer

TRAFFIC BULLETIN NO. 7

DELAY TO TRAFFIC DUE TO FUTURE RESURFACING OPERATIONS

NOVEMBER, 1963

Prepared By:

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INTRODUCTION

Headquarters Traffic Department, in cooperation with various Districts, has been conducting a "Statewide Study of Delay to Traffic Due to Lane Closures During Construction Operations" for the purpose of gathering information to be used in estimating delays to traffic during future resurfacing operations. The information presented here was developed through observations of various construction projects involving lane closures. Projects studied included 4, 6, and 8 lane freeways mostly in the larger metropolitan areas.

It was found that the delay encountered in these studies could be grouped into two categories:

1. Where the flow of traffic is below the capacity of the restricted roadway, the traffic will continue to be in a free-flow condition with only minor delay caused by the presence of workers and equipment in the area and reduced speed limits.

2. Where the rate of flow of traffic exceeds the capacity of the restricted section, a queue will form upstream resulting in quite a large delay.

Except in the large metropolitan areas, or other places where flow approaches the capacity of the facility, it is anticipated that most delays encountered will fall into the first category.

Part I of this paper deals with the development of a theoretical way to calculate a delay caused by a queue. The actual delays as calculated for many of the projects were compared with this theoretical method and the results were found to be quite close.

Part II, Calculation of Delay, explains the procedure to be followed in calculating the delay to traffic due to closing a lane for resurfacing operations. This section is divided into two parts--(a) Delay to traffic due to reduced speed, and (b) Delay due to a queue. For the delay caused by a queue, both a formula and graph will be presented in order to calculate these delays on 4, 6, and 8 lane facilities.

In the last section, Part III, an example calculation of a delay is presented. In this example, both the delay due to a reduction in speed through the area and the delay due to a queue will be discussed.

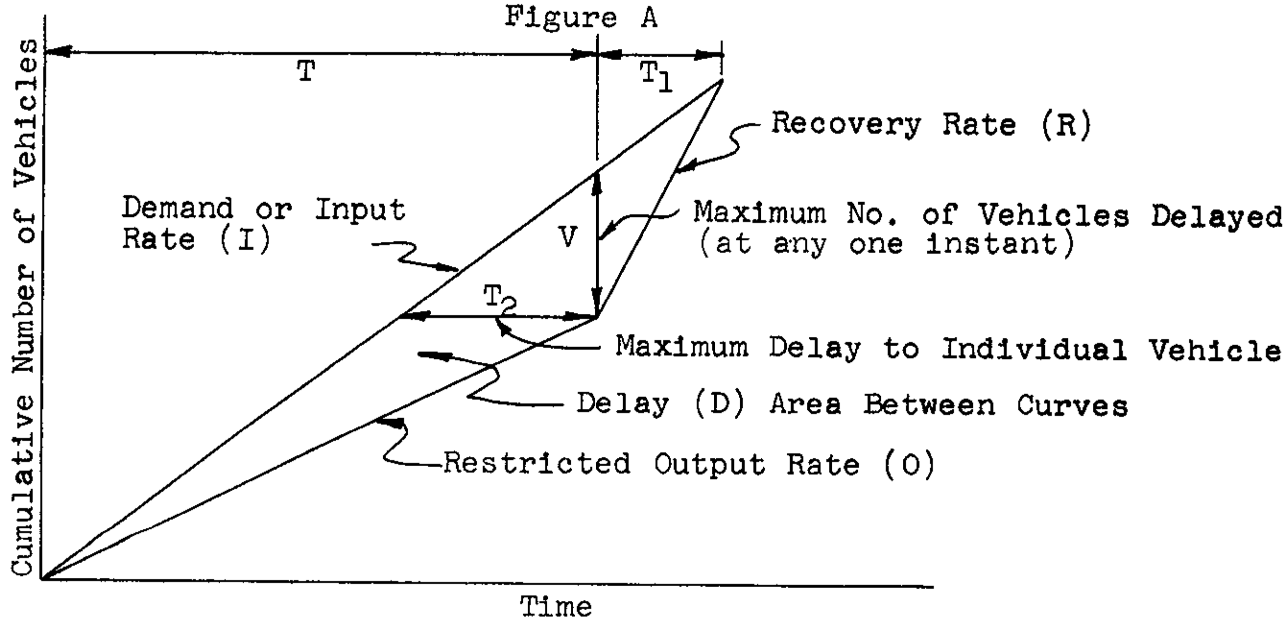
The information presented in this Bulletin is to be used as a guide in making predictions concerning traffic delays due to future resurfacing operations.

PART I - DEVELOPMENT OF DELAY FORMULA

Results of the "Statewide Delay Studies" have proved that the following theoretical method for calculating a delay caused by a traffic queue is fairly accurate. It should be understood that in practice, the demand or input rate will not remain absolutely constant during the period of lane closure. However, the assumption of a constant input rate when applied to future forecasts will usually be as accurate as assumptions regarding variable rates.

Figure A shows the relation between capacity and delay when demand rate-of-flow exceeds capacity. It should be noted in Figure A that the Delay D is represented by the area between the two curves. The following formulas for calculating a delay are based on a constant input rate. If variable input rates are used during the day, curves should be plotted similar to Figure A and the area planimetered to obtain the delay.

Figure A



I = Demand or input rate in veh./hr.

O = Restricted output rate in veh./hr.

R = Recovery rate in veh./hr.

T = Length of time of lane restriction in hours.

T_1 = Length of time to recover to normal in hours.

V = Maximum no. of vehicles delayed (just before lane restriction is removed).

T_2 = Maximum delay to an individual vehicle in hours.

D = Delay in veh.-hrs.

Based on Figure A, it can be seen that V, the maximum number of vehicles delayed, can be expressed as follows:

$$V = IT - OT = T(I-O)$$

The time required for traffic to return to normal conditions (T_1) is:

$$RT_1 = V + IT_1$$

substitution of $V = T(I-O)$ in the above equation gives:

$$RT_1 = T(I-O) + IT_1$$

$$RT_1 - IT_1 = T(I-O)$$

$$T_1(R-I) = T(I-O)$$

$$\text{and } T_1 = \frac{T(I-O)}{R-I}$$

It can be seen from the above equation that in order to calculate the recovery time, you will have to know the length of time the lane will be restricted (T) and the input rate (I). The output rate (O) during restriction and recovery rate (R) will be given for the particular type of facility studied, that is 4, 6, or 8 lanes.

The total Delay for the period of lane restriction (T) and the recovery period (T_1), is represented by the area between the two curves.

$$D = \frac{TV}{2} + \frac{T_1 V}{2} = \frac{V(T + T_1)}{2}$$

Substitution of V = T(I-O) in the above equation gives:

$$D = \frac{T}{2}(I-O)\ (T+T_1)$$

and further substitution of $T_1 = \frac{T(I-O)}{R-I}$

will give:

$$D = \frac{T}{2}(I-O)\ \left(T+T\left(\frac{I-O}{R-I}\right)\right)$$

and

$$D = \frac{T^2}{2}\ (I-O)\ \left(1 + \left(\frac{I-O}{R-I}\right)\right)$$

The maximum delay to an individual vehicle (T_2) can be calculated as follows:

$$T_2 I = V = T(I-O)$$

and $T_2 = \frac{T}{I}(I-O)$

Part II (B) of this Bulletin presents these same formulas along with appropriate output rates (O), and recovery rates (R) for the various multi-lane facilities. In addition, graphical solutions of the delay equation are also included.

PART II - CALCULATION OF DELAY

The delay to traffic due to a lane closure is to be estimated in two steps. Delays determined in these 2 steps should be added to each other to obtain the total delay. In the first step (Part A below), the delay due to a reduced speed through the construction area is to be estimated. In the second step (Part B) the delay due to a queue is calculated.

A. DELAY TO TRAFFIC DUE TO REDUCED SPEED

The delay encountered due to a reduced speed through the construction area is caused by:

(a) A posted speed limit in the construction area.

(b) Or a slow down due to the presence of workers and equipment in the construction area.

The following is a suggested procedure in calculating this delay:

1. Estimate the average speed at which traffic flows through the area under normal conditions (no lane closure). Also estimate the speed at which traffic will travel during the lane closure.

2. Determine the length for the lane restriction and a duration of time of lane restriction (T).

3. Estimate the traffic flow rate (input rate I, in one direction) during the period of lane closure. In most cases the resurfacing operation will probably be limited to daylight conditions during the off-peak

hours in order to avoid heavy congestion.

4. Estimate the percent trucks. If truck counts are available for the location in question, that information can be used in making this estimate. It should be pointed out that truck percentages are usually higher during the daylight off-peak hours than the average for the entire 24-hour period.

5. Knowing the difference in required travel times and the length of the construction area, calculate the delay to each vehicle. Using the proper flow rate* through the lane restriction, the delay to each vehicle, the percent trucks, and the duration of lane restriction, calculate the total delay for the duration of construction activities.

6. Apply the appropriate unit cost factors to obtain the total cost of delay. Use 8 cents a minute for the cost of delay to trucks, and 3 cents a minute for the value of a passenger-vehicle minute (See Circular Letter No. 61-222).

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*The input rate should be checked against the capacity shown in Table 1. If the input rate exceeds the output rates shown, use the appropriate output rate in Table 1 for calculating this delay.

Table 1.

CAPACITY TABLE (Input rates greater than the output rates listed will normally result in the formation of a queue.)					
Percent Trucks	No. of Lanes One Direction (Normal Operations)		2	3	4
	No. of Lanes One Direction (Restricted Operations)		1	2	3
0 - 10	Output Rate	O	1400	2800	4500
	Recovery Rate	R	3000	4700	6400
Over 10	Output Rate	O	1350	2700	4350
	Recovery Rate	R	3000	4500	6200

Note: The rates as listed above are veh/hr in one direction.

For the most part, the flow rates listed in Table 1 are based on data collected on observed lane closures which had a high truck volume and in some cases were located in the vicinity of uphill grades (overhead and undercrossing structures) and may appear to be low. It is believed that as the drivers become accustomed to the lane closure and with an improved transition at the point of merge, these rates could be higher. Every effort should be made to insure that a smooth transition exists. Therefore, under certain conditions, the rates listed may be varied slightly to meet particular situations.

B. DELAY DUE TO QUEUE

In addition to the delay caused by a reduction in speed through the construction area, there may be an additional delay due to a traffic queue.** Normally, only the larger metropolitan areas will encounter this type of delay and even in those areas only the facilities with higher volumes of traffic should be affected.

** The delay caused by a reduction in speed through the construction area is addable to the delay in queue, since this delay occurs downstream of the queue.

The following procedure should be followed in calculating the delay caused by a traffic queue:

1. Determine if a queue will be formed. Using the previously determined input rate (I) and the percent trucks, enter the Capacity Table (Table 1) with the appropriate number of lanes involved to determine whether or not a queue will be formed. A queue will be formed if the estimated input rate (I) exceeds the output rate (O) listed in the table.

2. If it has been determined that a queue will form, select the appropriate delay formula from the attached figures. Using the duration of lane restriction (T) and the input rate (I) from Steps 2 and 3 above, calculate the delay. The formulas presented in the figures are the same as developed in Part I, with the output rate (O) and recovery rate (R) already incorporated in each formula. Expand this delay for the duration of the project.

The delay formulas listed in the attached figures are based on the assumption that the input rate (I) is constant throughout the day. If instead, a variable flow rate is used, a plot will have to be made similar to Figure A and the area between the curves planimetered to obtain the delay. It is suggested that even though the input rate is constant during the time of lane restriction that the curves be plotted as a check.

3. Apply the appropriate unit cost factors to each class of vehicle to obtain the total cost of this delay.

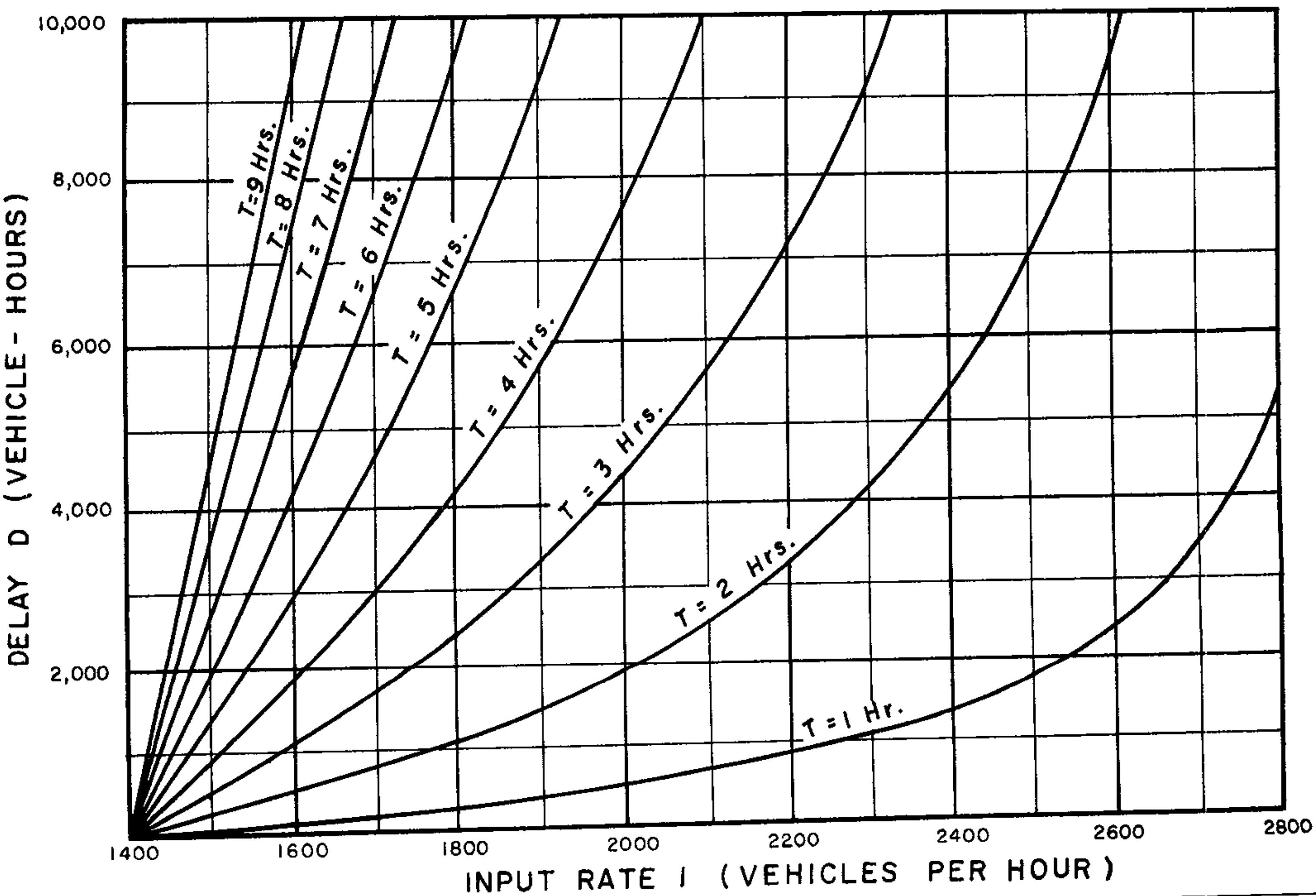
Various other formulas in the tables may be useful in the analysis of proposed resurfacing projects. The maximum delay to an individual vehicle (T_2) as well as the maximum number of vehicles delayed (V) can be predicted. This information may be helpful in determining just how far the queue will extend. The length of queue may be a controlling factor in setting the duration of lane closure (T). The time required for traffic to return to a free flow or normal condition (T_1) can also be estimated. This time may also be useful in arriving at a period of lane closure such that peak hour traffic can be avoided.

As stated previously, the formulas and various flow rates presented here were developed from results obtained from the "Statewide Study of Delay to Traffic". These figures represent the averages of observations made on typical construction projects.

DELAY CHART

<table>
<tr><th colspan="2">4 LANE FREEWAYS
(2 lanes in one direction normal operations, restricted to one lane)</th></tr>
<tr><td>For use when I > 1400 and from 0 to 10% Trucks</td><td>For use when I > 1350 and over 10 % Trucks</td></tr>
<tr><td>$V = T(I-1400)$
$T_1 = \frac{T(I-1400)}{(3000-I)}$
$T_2 = \frac{T(I-1400)}{I}$
$D = \frac{T^2}{2}(I-1400)\left[1+\frac{(I-1400)}{(3000-I)}\right]$</td><td>$V = T(I-1350)$
$T_1 = \frac{T(I-1350)}{(3000-I)}$
$T_2 = \frac{T(I-1350)}{I}$
$D = \frac{T^2}{2}(I-1350)\left[1+\frac{(I-1350)}{(3000-I)}\right]$</td></tr>
<tr><td colspan="2">V: Maximum No. of vehicles delayed.
T_1: Length of time reguired to recover to normal in hrs.
T_2: Maximum delay to an individual vehicle in hrs.
D: Delay in vehicle - hours.
I: Demand or input rate in veh. per hr. in one direction.
T: Duration of lane restriction in hrs.</td></tr>
</table>

Note: The chart presented below is for use when I > 1400 and from 0 to 10% Trucks.



DELAY CHART

6 LANE FREEWAYS (3 lanes in one direction normal operations, restricted to 2 lanes)	
For use when $I > 2800$ and from 0 to 10% Trucks	For use when $I > 2700$ and over 10% Trucks
$V = T(I-2800)$ $T_1 = \frac{T(I-2800)}{(4700-I)}$ $T_2 = \frac{T}{I}(I-2800)$ $D = \frac{T^2}{2}(I-2800)\left[1+\frac{(I-2800)}{(4700-I)}\right]$	$V = T(I-2700)$ $T_1 = \frac{T(I-2700)}{(4500-I)}$ $T_2 = \frac{T}{I}(I-2700)$ $D = \frac{T^2}{2}(I-2700)\left[1+\frac{(I-2700)}{(4500-I)}\right]$

V = Maximum No. of vehicles delayed.
T_1 = Length of time required to recover to normal in hrs.
T_2 = Maximum delay to an individual vehicle in hrs.
D = Delay in vehicle - hours.
I = Demand or input rate in veh. per hr. in one direction.
T = Duration of lane restriction in hrs.

Note: The chart presented below is for use when I > 2800 and from 0 to 10% Trucks.

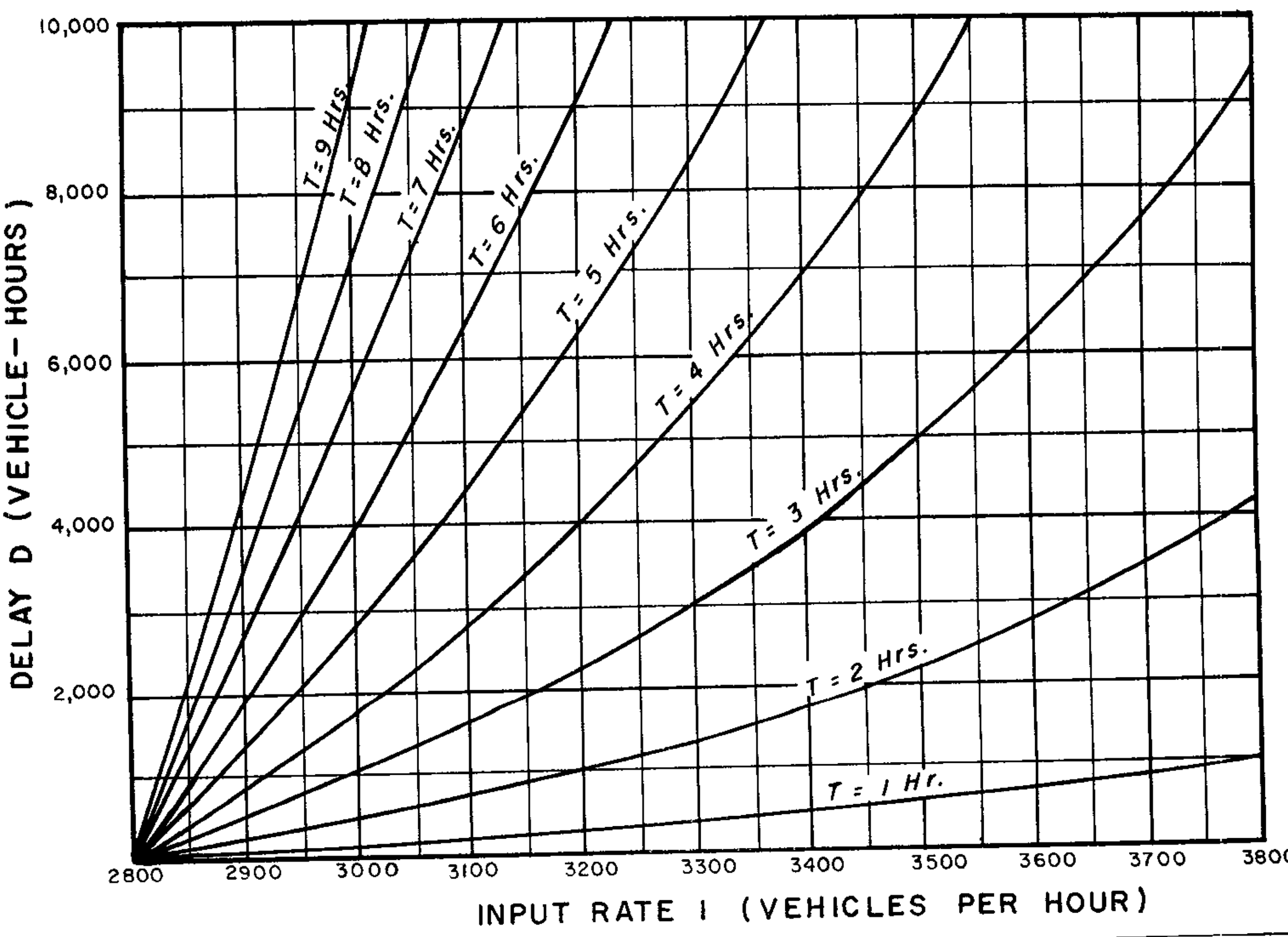


Figure 3

DELAY CHART

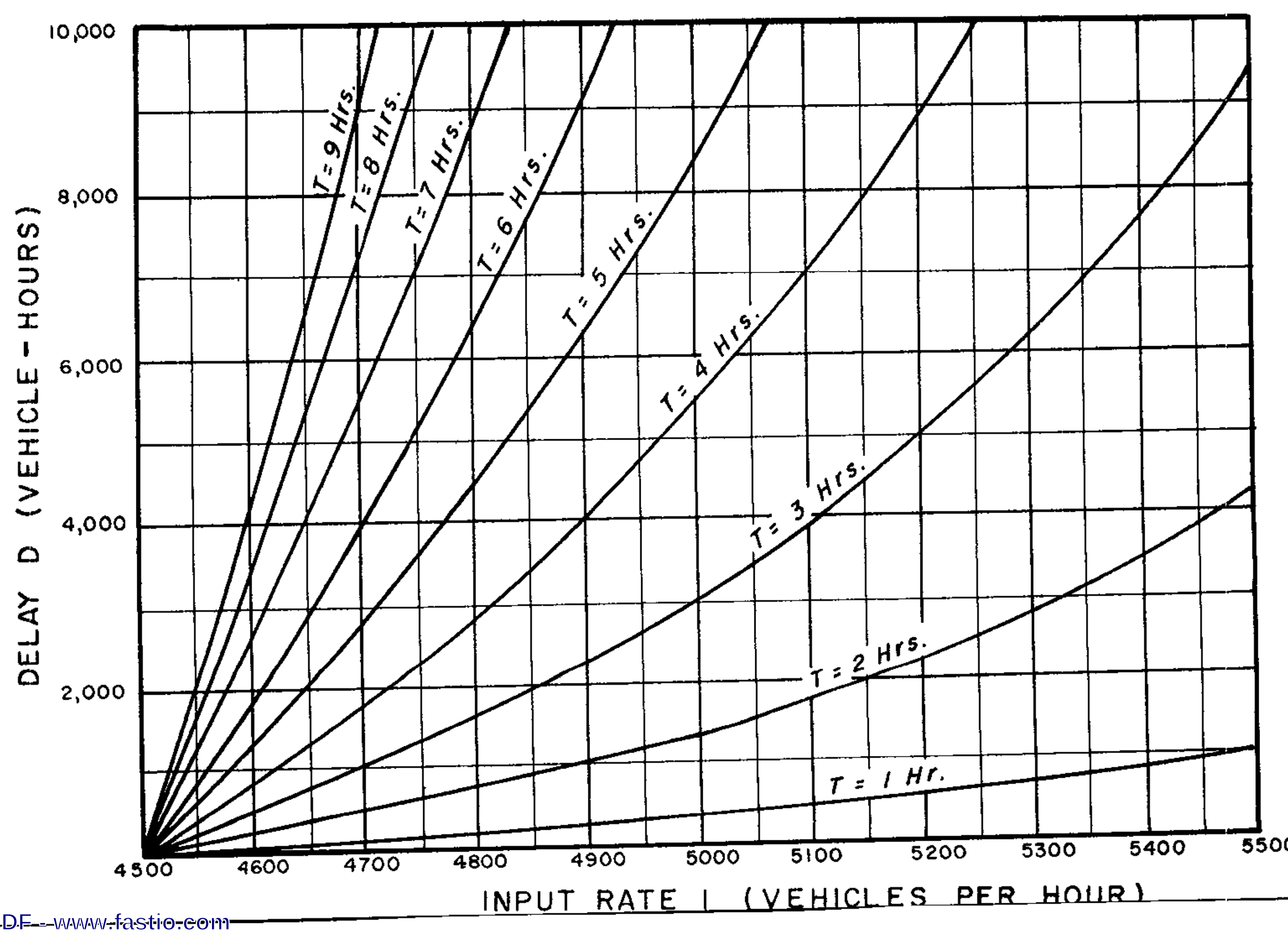
8 LANE FREEWAYS

(4 lanes in one direction normal operations, restricted to 3 lanes)

For use when $I > 4500$ and from 0 to 10% Trucks	For use when $I > 4350$ and over 10% Trucks
$V = T\,(I-4500)$	$V = T\,(I-4350)$
$T_1 = \frac{T\,(I-4500)}{(6400-I)}$	$T_1 = \frac{T\,(I-4350)}{(6200-I)}$
$T_2 = \frac{T}{I}(I-4500)$	$T_2 = \frac{T}{I}(I-4350)$
$D = \frac{T^2(I-4500)}{2}\left[1+\frac{(I-4500)}{(6400-I)}\right]$	$D = \frac{T^2(I-4350)}{2}\left[1+\frac{(I-4350)}{(6200-I)}\right]$

V = Maximum No. of vehicles delayed.
T_1 = Length of time required to recover to normal in hrs.
T_2 = Maximum delay to an individual vehicle in hrs.
D = Delay in vehicle - hours.
I = Demand or input rate in veh. per hr. in one direction.
T = Duration of lane restriction in hrs.

***Note*:** The chart presented below is for use when $I > 4500$ and from 0 to 10% Trucks.



PART III - EXAMPLE

The following is an example of a delay calculation:

The project is to consist of resurfacing six miles of a six-lane urban freeway (in both directions). The predicted ADT at the time of resurfacing is 104,000. Due to heavy peak hour traffic, construction operations are to be limited to the off-peak hours between 0900 and 1600. The percent trucks during the off-peak hours is estimated at 14%. The contractor is required to limit his paving operations to one lane. In addition, no more than one mile in length may be closed to traffic at a time. Traffic will be required to slow to 40 MPH through the construction area.

A. Calculation of delay due to reduced speed.

1. The estimated average speed of traffic under normal conditions is 56 MPH for autos and 48 MPH for trucks. As stated above, the reduced rate through the construction area will be 40 MPH.

2. As stated above, the length of lane closure is to be limited to one mile while the period of lane restriction will be seven hours.

3. It is estimated (for this example) that the off-peak hourly volume will be 5-1/2% of the ADT.

.055 x 104,000 = 5,720 vehicles per hour (in both directions).

It is further assumed that there will be an equal split in traffic by direction.

Therefore, the input rate (I) is:

$\frac{5720}{2}$ = 2860 vehicles per hour (in one direction)

4. Delay to each individual vehicle.

(Autos) Normal travel time

$\frac{1.0 \text{ mi.}}{56 \text{ mi/hr.}} \times 3600 \text{ sec/hr.} = 64 \text{ sec.}$

Restricted travel time

$\frac{3600}{40} = 90 \text{ sec.}$

90 - 64 = 26 sec. delay

(Trucks) $\frac{3600}{40} - \frac{3600}{48} = 15$ sec. delay

5. The estimated percent trucks, as stated above is 14%.

6. Calculations of delay.

A check of the Capacity Table with an input rate of 2860 vehicles per hour and 14% trucks, indicates that delay due to a queue will be encountered. Therefore, the output rate (O) of 2700 vehicles per hour should be used in this calculation instead of the input rate of 2860.

(Autos)

2700 veh/hr x .86 x 7 hrs x $\frac{26 \text{ sec.}}{3600 \text{ sec/hr}}$ = 117 veh-hrs

(Trucks)

2700 x .14 x 7 x $\frac{15}{3600}$ = 11

DAILY DELAY DUE TO REDUCED SPEEDS = 128 veh-hrs.

It is assumed that the contractor can pave two miles of 1" by 12' A.C. blanket in the seven hour construction period. Therefore, the total time allotted for the contract is:

$$\frac{6 \text{ miles}}{2 \text{ miles/day}} \times 6 \text{ lanes} = 18 \text{ days}$$

The total delay for the period of construction is:

(Autos) 18 x 117 = 2,106 veh.-hrs.

(Trucks) 18 x 11 = 198 veh.-hrs.

2,304 veh.-hrs.

7. Total cost of a delay due to reduced speeds.

(Autos) 2106 x 60 x \$.03 = \$3,791

(Trucks) 198 x 60 x \$.08 = 950

\$4,741

B. Calculation of delay due to a traffic queue.

1. Calculation of Delay

Since it was previously determined that there would be a queue formed (Step 6 above) select the appropriate delay formula from Figure 2 (for 6-lane freeways). With (I) greater than 2700 and over 10% trucks, the correct formula for delay is:

$$D = \frac{T^2}{2}(I-2700)\left[1 + \frac{(I-2700)}{(4500-I)}\right]$$

Therefore, substitution of T = 7 hrs. and I = 2860 gives:

$$D = \frac{7^2}{2}\ (2860 - 2700)\left[1 + \frac{(2860 - 2700)}{(4500 - 2860)}\right]$$

$$D = \frac{49}{2}\ (160)\left[1 + \frac{160}{1640}\right] = 4302 \text{ veh-hrs per day}$$

18 x 4,302 = 77,436 total veh-hrs.

(Autos) 77,436 x .86 = 66,595 veh-hrs.

(Trucks) 77,436 x .14 = 10,841 veh-hrs.

2. Total cost of delay due to queue.

(Autos) 66,595 x 60 x $.03 = $119,871

(Trucks) 10,841 x 60 x $.08 = 52,037

$171,908

It is to be noted that in this example, a constant input rate of 2860 vehicles per hour was used for the entire day. If, instead, variable flow rates are used, a graph should be plotted similar to Figure A (Part I) and the area between curves planimetered to obtain the delay.

C. Total Cost of Delay.

Delay due to reduced speed	=	$4,741
Delay due to queue	=	171,908
TOTAL		$176,649
Use		$176,600

D. Cost per three-lane mile.

As requested in Circular Letter No. 63-169, dated June 24, 1963, concerning the "Economic Comparison of Pavement Types", the final figure representing the cost of a delay due to resurfacing operations is to be submitted on the basis of a two-lane mile, three-lane mile, etc. Therefore, the above answer should be presented on the per three-lane mile basis.

$$\frac{\$176,649}{6 \text{ mi. } x \text{ } 2 \text{ directions}} = \$14,721 \text{ per 3-lane mile}$$

Use $14,700

If it is desired, the above calculation could have been made on this basis in the beginning, thus eliminating several of the steps involved in calculating the total cost of delay. Referring to Figure 2, the following added information can be obtained:

The maximum number of vehicles delayed is estimated using the following formula:

$V = T(I-2700) = 7(2860 - 2700) = 1120$ vehicles

The time required to recover to normal once the lane restriction has been removed can be estimated by the following:

$$T_1 = \frac{T(I-2700)}{(4500 - I)} = \frac{7(2860 - 2700)}{(4500 - 2860)} = .68 \text{ hrs.}$$

or 41 minutes.

The maximum delay to an individual vehicle would be:

$$T_2 = \frac{T}{I}(I - 2700) = \frac{7}{2860}(2860 - 2700) = .39 \text{ hrs.}$$

or 23 minutes.

F. Graphical solution of delay due to a queue.