Delay Analysis for Freeway Corridor Surveillance, Communication, and Control Systems

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A method of estimating the delay savings due to installation of a freeway corridor surveillance, communication, and control (SC&C) system is discussed. Using reasonable assumptions, the model estimates recurrent delay by speed-flow relationships and includes the effects of diversion to the frontage road. The nonrecurrent delay savings is found by using a graphical technique on a plot of time versus cumulative vehicles. The model parameters are easily adjusted for local conditions. The model provides a valuable tool for ranking SC&C projects and obtaining an estimate of their benefits.

In a research project conducted by the Texas Transportation Institute for the Texas Department of Highways and Public Transportation and completed in 1983 a methodology was developed for estimating the delay savings due to geometric improvements to an existing highway (*1*). Using a 20-year life, this model provides a cost-benefit ratio for a highway project and is currently being used in Texas to rank construction projects by priority.

A separate model developed to analyze freeway corridor surveillance, communication, and control (SC&C) systems is discussed here. Like the geometric model, the primary intent of this model is to provide an objective method of ranking construction projects and it contains many of the basic assumptions of the geometric model to ensure compatible results. The model requires only data that are commonly available in the planning stage of a project.

An SC&C system helps to provide safer and more efficient traffic operation by monitoring the traffic flow and, in case of congestion, controlling the traffic and helping clear the congestion. The principal elements of an SC&C system are surveillance loops and cameras, ramp metering, and a responsive signal system. The surveillance loops and cameras serve to alert an operator to a congested condition on the freeway. The operator can then use the ramp metering to divert traffic off the freeway onto the frontage road (or parallel street). In order to handle this increased traffic, the signal timings along the frontage road are adjusted to increase capacity and minimize delay.

The model calculates both the recurrent and the nonrecurrent delay saved by an SC&C system. Recurrent delay occurs every day at the same time of day and for the same length of time, barring normal statistical differences from day to day. The chief examples of recurrent delay are the morning and evening peak hours. Nonrecurrent delay is caused by an incident that is not expected, generally an accident or a stalled vehicle. Studies in California indicate that nonrecurrent delay can exceed the recurrent delay on a typical freeway (*2*).

Inputs to the model include the present and 20th-year average daily traffic (ADT), the number of lanes on the freeway and frontage road, the length of the project, and the cost of the SC&C system. The ADT is taken at a typical spot in the freeway section and ramp locations, and volumes are not handled explicitly. The model uses these very gross inputs to estimate the delay savings due to an SC&C system.

GENERAL OPERATION

Using the present and 20th-year ADT, an ADT for each of the 20 years of the project's life is found by using a logarithmic-type growth curve (*1*).

$$ADT_t = ADT_c(t + 1)^e$$

where

ADT_t = estimated ADT for year t;
ADT_c = current ADT, year 1;
e = $[\ln(ADT_p) - \ln(ADT_c)] / \ln(T)$;
ADT_p = projected ADT for year T; and
T = year at end of planning horizon = 20.

In finding the recurrent delay, typical K-factors for urban Texas freeways are used to determine the hourly volumes from the ADT (*1*). The directional distribution is assumed to be 50 percent. The hourly traffic is then distributed between the frontage road and the freeway, and average speeds are found for each by using some speed-flow relationships. If a queue exists at the end of the hour, it is carried over into the next hour. The traffic volume is multiplied by the length of the freeway section and divided by the average speed to obtain the total travel time. This is done for both the uncontrolled and the controlled freeway and the difference represents the recurrent delay savings for the day. To find the

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nonrecurrent delay, an analytical version of the graphical method shown in Figure 1 is used as described later (*3*). Once again, the delay is found for both the uncontrolled and the controlled freeways, and the nonrecurrent delay savings is the difference.

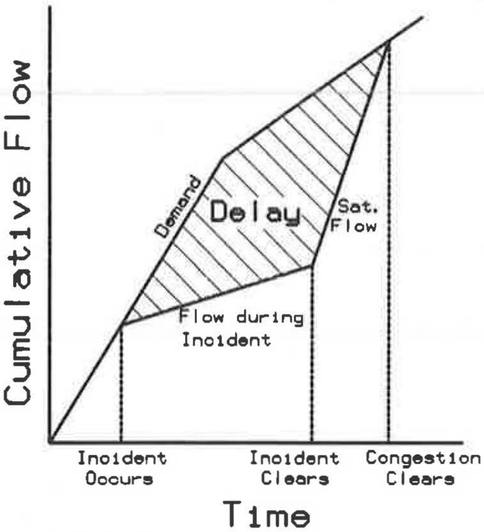

FIGURE 1 Nonrecurrent delay.

The total daily delay savings for each of the 20 years is then factored up to an annual savings. These 20 annual delay savings are then converted to monetary values and discounted to obtain the present value of the delay savings. Dividing by the cost of the system produces a benefit-cost ratio. The following sections give a further description of how the model works.

DISTRIBUTION OF TRAFFIC

The following parameters and variables are used:

q_T	=	total hourly flow [vehicles per hour (vph)],
q_M	=	flow + average queue on main lanes (vph),
q_F	=	flow on frontage road (vph),
s_0	=	queue at beginning of the hour (vehicles),
s_1	=	queue at end of the hour (vehicles),
N_M	=	number of main lanes,
N_F	=	number of frontage-road lanes,
Q_M	=	main-lane capacity [vph per lane (vphpl)],
Q_B	=	main-lane capacity after breakdown (vphpl),
Q_F	=	frontage-road capacity (vphpl),
Q_{FB}	=	frontage-road volume during main-lane breakdown (vphpl),
δQ_M	=	main-lane volume at which diversion to frontage road begins (vphpl),
γQ_B	=	used after main-lane breakdown; main-lane volume + average queue above which frontage road is fully loaded (vphpl), and
θQ_B	=	used after main-lane breakdown; main-lane volume + average queue at which there would be no vehicles on frontage road (vphpl).

Given the hourly traffic determined by the ADT and the assumed *K*-factors, the first step to finding the recurrent delay is to distribute the traffic between the freeway and the frontage road. Typical diversion curves used are shown in Figure 2. Basically, the freeway will carry all the traffic until the hourly volume reaches a certain point ($N_M \delta Q_M$). Between this point and until the main lanes reach capacity ($N_M Q_M$), the frontage road will carry an increasing portion of the total traffic. When the main lanes reach capacity, the main-lane breakdown and a new set of curves are used.

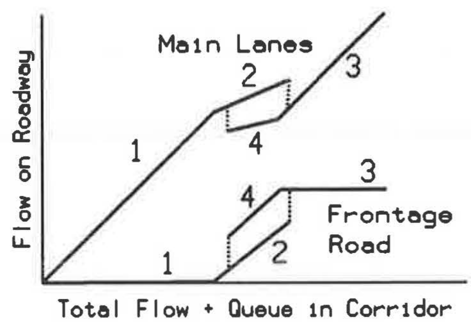

FIGURE 2 Typical diversion curves.

Rather than the hourly flow, the flow plus average queue is used after breakdown to account for the effect of a standing queue (*1*). As long as the flow plus average queue stays above $N_M \gamma Q_B + N_F Q_F$, both the main lanes and the frontage road will be operating at capacity. If the main-lane flow falls below $N_M Q_B$, the main lanes will recover and the other set of diversion curves will be used. Between these two points, traffic will begin diverting from the frontage road back to the main lanes, leaving the frontage road underutilized.

These general statements lead to the following equations. If the main lanes are not broken down, and $q_T < N_M \delta Q_M$ (Region 1 on Figure 2), then

$$q_F = 0$$
$$q_M = q_T - q_F$$
$$= q_T$$

If $q_T \leq (N_M Q_M + N_F Q_{FB})$ (Region 2), then

$$q_F = N_F Q_{FB} * (q_T - N_M \delta Q_M) \,/\, [N_F Q_{FB} + N_M Q_M (1 - \delta)]$$
$$q_M = q_T - q_F$$

If $q_T > (N_M Q_M + N_F Q_{FB})$, then the main lanes break down.

If the main lanes have broken down, and q_T + average queue $> (N_F Q_F + N_M \gamma Q_B)$ or if $1.5 q_T + s_0 > 1.5 N_F Q_F + N_M Q_B (\gamma + 0.5)$ (Region 3), then

$$q_F = N_F Q_F$$
$$s_1 = s_0 + q_T - N_M Q_B - N_F Q_F$$
$$q_M = q_T - q_F + 0.5(s_0 + s_1)$$

If $1.5 q_T + s_0 > 1.5 N_M Q_B + 1.5 N_F Q_F (1 - \theta) \,/\, (\gamma - \theta)$ (Region 4), then

$$q_F = N_F Q_F * [1.5 q_T + s_0 - N_M Q_B(\theta + 0.5)] \, / \, [1.5\, N_F Q_F + N_M Q_B (\gamma - \theta)]$$
$$s_1 = s_0 + q_T fa - q_F - N_M Q_B$$
$$q_M = q_T - q_F + 0.5(s_0 + s_1)$$

If $1.5 q_T + s_0 < 1.5 N_M Q_B + 1.5 N_F Q_F (1 - \theta) \, / \, (\gamma - \theta)$, then the main lanes recover.

SPEED-FLOW RELATIONSHIPS

The following parameters and variables are used:

q_M = flow + average queue on main lanes,
q_F = flow on frontage road,
u_M = speed on main lanes (mph),
u_F = speed on frontage road (mph),
N_M = number of main lanes,
N_F = number of frontage-road lanes,
U_{MF} = main-lane free-flow speed (mph),
U_{MC} = main-lane speed at capacity (mph),
U_B = main-lane and frontage-road speed under forced flow (mph),
U_F = frontage-road free-flow speed (mph),
S_{MA} = slope of main-lane curve in Level-of-Service (LOS) A-D range (miles/vehicle),
S_{ME} = slope of main-lane curve in LOS E range (miles/vehicle),
S_{FA} = slope of frontage-road curve in LOS A-D range (miles/vehicle),
Q_M = main-lane capacity (vphpl),
Q_B = main-lane capacity after breakdown (vphpl),
γQ_B = used after breakdown; main-lane flow + average queue at which speeds start to increase (vphpl),
Q_F = frontage-road capacity (vphpl), and
Q_{FD} = LOS D/E breakpoint for frontage road (vph).

After the flow plus average queue has been obtained for both the main lanes and the frontage road, speed-flow curves are used like those in Figure 3. These curves are easy to use and do not require explanation. The main lanes use different curves for congested and uncongested conditions to allow greater flexibility in adjusting the response of the model.

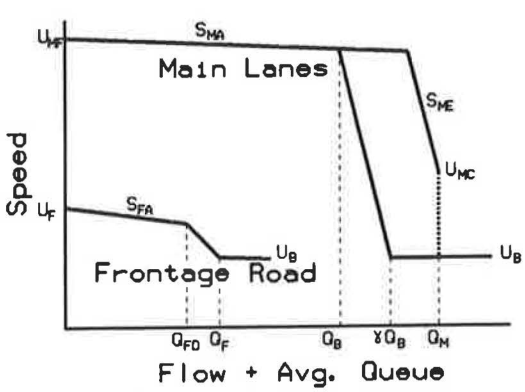

FIGURE 3 Typical speed-flow curves.

SIMULATING EFFECTS OF SC&C SYSTEM

There are five mechanisms in the model that differentiate between the operation of an uncontrolled freeway and a controlled one. The first deals with diversion of traffic to the frontage road before the main-lane breakdown. On a controlled freeway, the surveillance system will detect the freeway approaching congestion and the system will use the ramp metering to divert traffic to the frontage road and help the freeway continue to operate smoothly. The model assumes, on the other hand, that there will be no diversion from an uncontrolled freeway until capacity is reached and the main lanes break down. The model uses δ and Q_{FB} to simulate this effect. δ is a factor applied to the main-lane capacity to indicate the point at which diversion starts. Q_{FB} is the volume on the frontage road when the main lanes break down.

There is also a difference in how traffic is diverted when the freeway is trying to recover. θ is a factor applied to the main-lane capacity after breakdown that indicates the main-lane volume at which all the frontage-road traffic would revert to the main lanes. Because there will generally be some traffic on the frontage road until the main lanes have completely recovered, this factor should be less than 1. A controlled system should, however, retain considerably more vehicles on the frontage road until recovery, and therefore θ should be lower for the controlled freeway.

Because of lessened turbulence at entrance ramps, a controlled freeway should have a larger main-lane capacity than an uncontrolled one. A study in Austin, Texas, showed a 10 percent increase in main-lane capacity by using ramp metering (B. G. Marsden, unpublished data). The model uses Φ as a factor to increase the main-lane capacity to reflect this.

There should also be an increased capacity along the frontage road, because a central signal system will be able to adjust to conditions and provide better service than isolated interchanges. It would also be possible to change the phasing sequence and offsets to enhance progression along the frontage road in cases of diversion leading to a higher free-flow speed as well as to higher capacity.

SENSITIVITY TESTING

Because of the large number of parameters, extensive testing was not possible on all of them. However, several key and questionable ones were chosen for sensitivity testing (Table 1). Those parameters that were tested over a range of values were analyzed at ADTs of 150,000; 160,000; 170,000; 180,000; 190,000; and 200,000 on a freeway with six main lanes and four frontage-road lanes. Most of the parameters that were tested over a range did not significantly affect the results. Three parameters were, however, significant. The most important was the main-lane capacity after breakdown (Q_B):

Q_B	*Hours of Delay Saved*
1,500	20,800
1,600	15,600
1,700	10,700
1,800	7,100

TABLE 1 PARAMETERS CHOSEN FOR SENSITIVITY TESTING

Parameter	Description	Value(s)	Source
Q_M	Main-lane capacity (vphpl)	1,800-2,000	HCM *(4)*
Φ	Factor to increase main-lane capacity for controlled system	1.05-1.15	Summer *(3)*
Q_B	Main-lane capacity after breakdown (vphpl)	1,500-1,800	HCM *(4)*
Q_F	Frontage-road capacity (vphpl)	800-900	HCM *(4)*
λ	Factor to increase frontage-road capacity for controlled system	1.25-1.35	
Q_{FB}	Frontage-road volume during main-lane breakdown (vphpl)	500-700	
δ	Factor applied to main-lane capacity to indicate when diversion to frontage road on controlled system begins	0.85-0.95	
γ	Factor applied to main-lane capacity after breakdown to obtain a capacity above which the frontage road is fully loaded	1.1-1.2	
θ	Factor applied to main-lane capacity after breakdown to obtain main-lane volume at which all frontage-road traffic would revert back to main lanes	0.80-0.95	
U_{MF}	Main-lane free-flow speed (mph)	60	Memmott *(1)*
U_{MC}	Main-lane speed at capacity (mph)	35	Memmott *(1)*
U_B	Main-lane and frontage-road speed under forced flow (mph)	15	Memmott *(1)*
U_{FC}	Controlled frontage-road free-flow speed (mph): LOS A for 45-mph arterial	35	HCM *(4)*
U_{FU}	Uncontrolled frontage-road free-flow speed (mph): LOS C for 45-mph arterial	22	HCM *(4)*
S_{MA}	Slope of main-lane speed curve in LOS A-D range	0.002	Memmott *(1)*
S_{ME}	Slope of main-lane speed curve in LOS E range	0.073	Memmott *(1)*
S_{FA}	Slope of frontage-road speed curve in LOS A-D range	0.012	Memmott *(1)*
Q_{FD}	LOS D/E breakpoint for frontage road (vphpl)	600	Memmott *(1)*

Note: HCM = Highway Capacity Manual; LOS = level of service.

The main reason for this is that the capacity after breakdown is very influential in determining the length of time that a queue will be present. Increasing it significantly decreases the hours of delay under an uncontrolled situation.

The increase in main-lane capacity due to ramp meter control (Φ) was also a significant parameter:

Φ	*Hours of Delay Saved*
1.05	18,600
1.10	20,800
1.15	25,700

The main-lane capacity (Q_M) also caused a significant change in the delay savings:

Q_M	*Hours of Delay Saved*
1,800	19,600
1,900	20,800
2,000	24,700

The major changes seen in these parameters are primarily due to isolated effects from using hourly flows. Over a 20-year analysis, these fluctuations would tend to even out.

Figure 4 shows how the recurrent delay savings behaves over a range of ADTs. At 250,000 ADT, the volumes are so large that both the controlled and the uncontrolled system spend most of the day queued up, thereby reducing the savings.

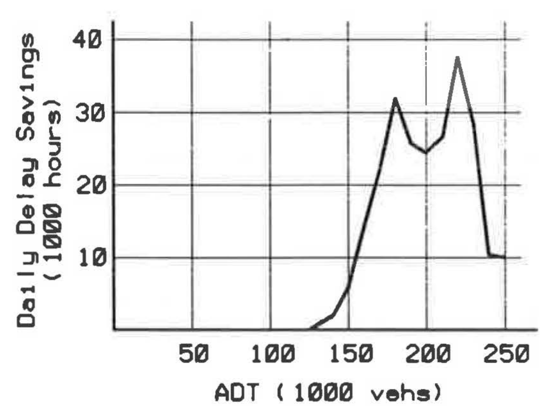

FIGURE 4 Recurrent delay savings over range of ADTs.

NONRECURRENT DELAY

In addition to the recurrent delay calculated by the foregoing procedure, nonrecurrent delay is taken into account. Nonrecurrent delay is most often due to a car that has run out of gas, a flat tire, or a minor accident. The *Freeway Management Handbook* estimates that there are 200 incidents of all types per million vehicle miles on freeways (*3*). The handbook also breaks down these incidents by type and gives the probability of each. Approximately 19 percent of these incidents block only the shoulder and require assistance to clear. Of the total number of incidents, 2.6 percent block one lane and require assistance, whereas only 0.093 percent block two lanes. Because of the low probability that an incident will block more than one lane, only shoulder and one-lane incidents are considered.

The handbook also contains guidelines on the capacity of freeway lanes when an incident is on the shoulder or in one lane. For shoulder incidents, capacity with two freeway main lanes is 3,000; three lanes, 4,600; and four lanes, 6,300. For incidents that block a lane, the capacity for a two-lane roadway is 1,300; three lanes, 2,700; and four lanes, 4,300. The capacity of the frontage road is assumed to be 750 vphpl for uncontrolled freeways and 1,000 vphpl for controlled ones.

In the Houston area, it is estimated that surveillance will shorten the response and clearance time of an incident from 35 to 30 min. That is, for the uncontrolled freeway, the period of blockage is 35 min, after which the queue is flushed out at the saturation flow of 1,850 vphpl for the main lanes and 750 vphpl for the frontage road. The controlled freeway is blocked for 30 min, after which the saturation flow is 1,850 vphpl for the main lanes and 1,000 vphpl for the frontage lanes.

Using the annual ADTs found earlier, a daily nonrecurrent delay savings is found by comparing the delay found on a controlled freeway corridor with that of an uncontrolled corridor. An average hourly flow is found for each 4-hr period of the day by using *K*-factors for a normal Texas urban section. The number of shoulder and one-lane incidents is then found for the hour by multiplying the number of vehicles by the length of the section by 0.0002 (200 incidents per million vehicle miles). The graphical technique shown in Figure 1 gives the delay for each incident.

For those incidents during lightly traveled hours that do not congest, it is also assumed that vehicles will travel 30 mph when there is an incident on the shoulder and 15 mph when it is in one of the lanes.

After the daily nonrecurrent delay has been calculated, it is added to the recurrent delay for a total daily delay, which is factored up to obtain the annual delay.

CONCLUSION

This model is intended as a tool to compare various SC&C projects and to obtain an estimate of their benefits. As such, it appears to perform quite well. Many of the assumptions made do not have solid field validation but represent reasonable values, and the sensitivity analysis indicates that the major parameter to be careful of is the capacity after breakdown. The methodology is adaptable and the parameters can be changed for various conditions, such as the use of a parallel street rather than a frontage road. In the context of a planning analysis, it performs admirably well.

ACKNOWLEDGMENT

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