Investigation of the Impacts of Ramp Metering on Traffic Flow With and Without Diversion

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The effect of various levels of ramp metering on traffic flow in a 7-mi-long urban corridor consisting of a freeway, two parallel surface arterials, and seven perpendicular connecting surface arterials was evaluated. The study was conducted both with and without traffic diversion from on-ramps to surface streets using the INTRAS freeway corridor simulation model. Three levels of ramp metering were analyzed to determine how much each would reduce the effects on traffic of an incident on the freeway. For each level of metering, several traffic diversion schemes were introduced in an incremental manner. The diversion of vehicles was implemented for each level of ramp metering until the remaining number of vehicles behind the meters was the same for each level and was less than the storage capacity of the ramp behind the meter. The main conclusion is that, whereas ramp metering improves the traffic flow on the freeway, it adversely affects the total system because of the overflow queues behind the meters, which spill back onto the surface streets. The only metering level that does not do this (in the absence of diversion) is one in which the metering rates are adjusted so that the overflow queues do not occur (equivalent to a queue detector at the upstream end of a ramp overriding the meter when a queue is detected). This level of metering, however, is rarely sufficient to overcome the capacity reduction resulting from an incident. To minimize the adverse effects of ramp metering, an appropriate traffic diversion plan for the implemented ramp metering strategy is required. The impacts on the total system under the optimum ramp metering and the best diversion plan consist of only a 4.1 percent increase in speed and a 10.5 percent decrease in delay.

Ramp metering controls the number of vehicles entering a freeway from on-ramps by subjecting the entry to a fixed-time or a traffic-responsive control similar to the conventional control provided by traffic signals. The purpose of such a control is to reduce the traffic demand onto the freeway to maintain adequate freeway traffic flow and to prevent the development of congestion on the freeway. The impacts of ramp metering on freeway traffic flow include increasing the traffic speed and the rate of mainline flow in terms of miles per hour and vehicles per hour per lane, respectively. If the demand at the metered ramp is higher than the discharge rate, a queue behind the signal will build up and eventually overflow onto the adjacent surface street. The occurrence, duration, and extent of overflow queues also depend on the available storage length between the meter and the surface street. Depending on the duration and the magnitude of overflow queues, delay and congestion will be introduced onto the surface street system. Another impact of ramp metering is that it induces traffic route diversion. This is because some motorists wishing to use metered ramps will divert either to unmetered on-ramps or to less restrictive metered ramps or will not travel on the freeway and make their trips exclusively on surface streets. Since the delays due to waiting behind a ramp meter are proportionally greater for short trips (i.e., one to three interchanges), these are the trips most likely to be diverted to surface streets.

The diversion of vehicles from on-ramps and freeways to surface streets is a major institutional concern for both city traffic officials and freeway agencies. Whereas the diverted vehicles help to reduce the delay due to queuing behind the meters on ramps and help to reduce overflow queues, they increase the traffic volume on the surface streets. This type of diversion, in the opinion of some transportation agencies, tends to "greatly reduce the delay in the corridor by simply removing some of the vehicles from the freeway" (*1*).

When vehicles divert in this manner, there is no documentation available that quantifies this delay reduction and compares it to the delay in the same case of ramp metering but without traffic diversion taking place. However, several studies and reports have documented the benefits of ramp metering with diversion relative to the "before" condition of no ramp metering. However, previous studies in this area do not treat the parallel surface streets that will handle the diverted traffic with the same level of detail as the freeway. For instance, many of them use a freeway simulation model together with a module that treats the alternate route only in terms of a given average speed with no consideration of the impacts of the diverted traffic. Unlike the previous studies, this study considers the surface street arterials with the same level of detail as the freeway. The purpose of this study is to investigate, through simulation, the impacts of ramp metering with and without diversion on traffic flow in an urban corridor and to examine, quantitatively, the effects of the most likely type of ramp metering–induced diversion. The study considers different levels of diversion induced by three levels of ramp metering operating at six ramps in an urban corridor.

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METHODOLOGY

A review of the literature on ramp metering and traffic diversion was undertaken. The subject of traffic diversion in ramp metering operations was not discussed in every acquired report of ramp metering experiences. However, some of these reports included information relevant to diversion, such as storage behind meters, ramp delays, and queues. Several reports discussed the changes in the traffic flow on surface streets in terms of volumes and speeds. Only a few studies (*2–4*) of ramp metering experiences included a quantitative comparison of measures of effectiveness (MOEs) between "after" conditions with diversions occurring and "before" conditions prior to the implementation of ramp metering.

Two studies (*5,6*) involved the use of simulation as a tool in evaluating the effect of diversion in general terms. One study (*5*) included simulation of a diversion strategy only from NY-495 to another freeway without ramp metering. The other study (*6*) of I-25 in Denver, Colorado, used a simulation technique to select the best alternative from several schemes involving ramp metering on different sections and diversion of different numbers of vehicles. Most of the reports that calculated the impacts of ramp metering considered only the freeway MOEs.

To achieve the purpose and objectives of the study, a real-world corridor was selected for simulating traffic flow under the various conditions. A review of the available simulation models indicated that the INTRAS (*7,8*) simulation model was the most appropriate for this type of study for the following reasons:

1. INTRAS is a microscopic model that has been validated for freeway traffic, including simulation of incidents, and has a microscopic surface street component equivalent to the NETSIM model that has been validated for simulating surface streets (*9*).
2. The INTRAS model simulates ramp metering and the effect of overflow queues at the interface between the links behind a ramp meter and the upstream surface streets.
3. The INTRAS model simulates a surveillance system and has a module for computing detector point processing, which can be used to follow the formation of queues behind the incident on the freeway.
4. Because the INTRAS model is microscopic, quantities such as capacity are an output rather than an input, which is the case with macroscopic models. This is an absolute requirement if we are to use the results of the model to determine the number of vehicles that must be metered to alleviate the effects of an incident lane blockage.
5. INTRAS explicitly models the origin-destination pattern on the freeway by assigning individual vehicles to destinations as they enter the freeway. Thus, the paths and strategies they must take to achieve the assigned destination are explicitly modeled. This is not true of any other model.

No other simulation model currently available satisfies these requirements.

The simulation approach, rather than actual field studies, was chosen for several reasons. Some of the MOEs needed in this study cannot be measured in field studies precisely or even adequately within reasonable time and cost constraints. These include the total travel time in vehicle hours and queuing delays. However, since INTRAS is a microscopic simulation model, it is possible to obtain precisely those MOEs that are difficult to collect in the field.

Another reason for using simulation is that, to achieve the objectives of this study, different schemes of traffic diversions involving variable numbers of diverted vehicles and different origin-destination patterns are required. Experimentation with various combinations of numbers of diverted vehicles, ramp metering rates, and origins and destinations of trips are impractical in field studies, especially during incident-caused congestion like the one considered in this study. Further, in a ramp metering system, diversion might take place immediately after implementation. Therefore, no time period involving metering without diversion of the same system will exist, and accordingly, no MOEs for this condition can be observed and measured for comparison.

The sequence of steps in this study's approach was as follows:

1. Select a real-world network (made up of a freeway with parallel and intersecting surface arterial streets) that provides closely spaced interchanges with both metered and unmetered on-ramps.
2. Code the selected network according to the INTRAS model coding procedures.
3. Revise the signal phase timings for all signalized intersections using the Webster method.
4. Perform the basic simulation, which represents the "before" condition to which all other cases will be referenced and compared.
5. Develop three levels of ramp metering at six on-ramps to reduce traffic congestion on the freeway.
6. For each level of ramp metering, develop a diversion scheme or schemes to help reduce any overflow queues resulting from ramp metering.
7. Investigate the impacts of each metering level diversion scheme.

THE NETWORK

To satisfy the method and purpose of this study, a real-world network was chosen. A 7-mi stretch of Route 22, the Garden Grove freeway, in Orange County, California, was selected for the study with a boundary encompassing two parallel and seven intersecting arterial surface streets with 28 signalized intersections. The two-way freeway section includes seven interchanges with 14 on-ramps and 14 off-ramps and has generally three through lanes in each direction. The nonincident level of service for the freeway was C and for the surface streets was in the range C to D, depending on the particular intersection. Figure 1 represents the total areawide network. This network was chosen for the following reasons: data were available (*10*), the network included both a freeway and surface streets, and the surface streets provided good alternate routes for diverting traffic.

No claim is made that this network is representative of freeway corridors around the country. On the contrary, the

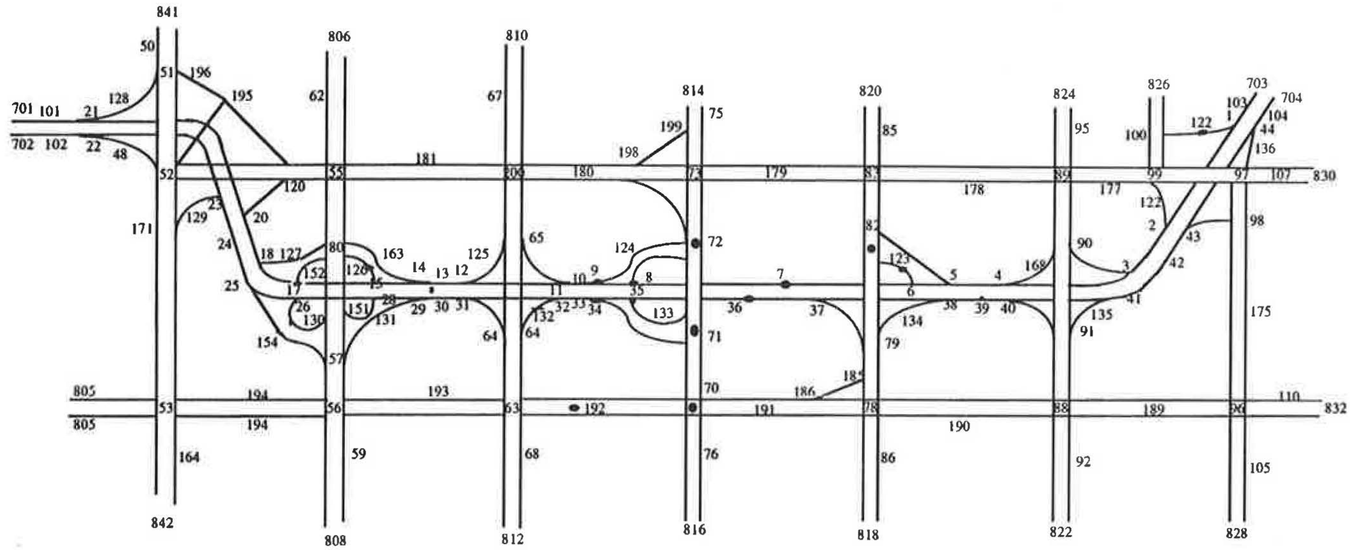

FIGURE 1 Garden Grove freeway network, Orange County, California.

situation relative to alternative routes is substantially better than most freeway corridors in the country. Therefore, it might be said that this network provides a "best case" opportunity for ramp metering with diversion. If no benefits can be obtained here, it is unlikely that they can be obtained anywhere else.

DESIGN OF SIMULATIONS

Basic traffic parameters had to be established and input into all simulations. These include the desired free-flow speed in each of the subsystems of the network and the mean queue discharge headway from signalized intersection approaches. The desired speed or the free-flow speed of the freeway was set at 65 mph, which represents the observed operating speed on the Garden Grove freeway, and was set at a speed of 35 mph for all entrance and exit ramps, which represents the observed operating speed on those facilities. The desired speed for all surface streets was set at 40 mph, representing the observed operating speed on the surface streets. For traffic discharging from a queue on off-ramps and surface streets, at signalized intersections, the mean queue discharge headway was set to 1.8 sec, on the basis of physical observations made when the data were originally collected (*10*). Finally, the duration of simulation was set at 90 min to allow the introduction of the incident, analysis of perturbations, system recovery, and other factors as discussed in a later section.

A no-incident simulation was established to represent the traffic flow in the network with the timings for the signal phases of intersections adjusted to produce the minimum possible delay. This case represents the "before" condition.

The various after conditions included an incident in the westbound direction. The location of the incident was determined so that the number of vehicles entering from the on-ramps and passing through the link where the incident occurred would be maximized. In reference to Figure 1, the incident, in which the right lane was blocked, was placed on Link 41-42. The trip origin-destination distribution from the no-incident simulation was used to calculate the number of vehicles destined downstream of the incident.

The characteristics of the incident, such as length of time, extent, type, and time of onset, were chosen to produce the congestion on the freeway that required restrictive ramp metering at several on-ramps. The recovery of the freeway traffic flow conditions to the preincident state was then evaluated, and on that basis the final basic simulation was established. Thus, a one-lane blockage lasting for 45 min of simulation and starting 15 min into simulation was selected.

Three levels of ramp metering were then designed for simulation. For each one, an appropriate number of diversion schemes were established.

Metering Level I: Restrictive Metering

The restrictive ramp metering plan was designed to reduce the demand at the incident site to the observed capacity (as measured by the no-metering INTRAS simulation) at the incident site. The metering plan was designed as follows:

1. From the origin-destination table in the output of the basic simulation, the demand on the incident link from each on-ramp was calculated.
2. The total number of vehicles per hour from each ramp to be metered passing through the incident site was obtained. (Some vehicles from upstream on-ramps will exit the freeway before the incident site. These vehicles must be accounted for in developing the metering plan.)
3. Each metered on-ramp contributes to reducing the demand as follows:

Reduction in demand at each ramp = $(V_1/V_2)(V_3)$

where

V_1 = total number of vehicles per hour to be reduced,
V_2 = vehicles per hour passing through incident link, and

V_3 = volume passing through incident link and originating from the on-ramp.

4. Subtracting the reduction in demand as calculated above at each metered on-ramp from its demand yields the volume that should be metered (discharged) from that ramp. Accordingly, the metering rate at each ramp was obtained in terms of release headways between vehicles (e.g., a metering rate of 600 vph is input as a 6-sec release headway in the model).

5. The constraints that affected the final determination of the ramp metering rate were (*a*) the INTRAS requirement that metering headways should be expressed in integers; (*b*) the maximum acceptable release headway, which was fixed as 18 sec for each metered vehicle, and thus the minimum metering rate was 200 vehicles per hour per lane; and (*c*) the minimum acceptable release headway, which was fixed as 5 sec (*11*) for each metered vehicle, so that the maximum metering rate was 720 vehicles per hour per lane.

First Diversion Scheme in Metering Level I

The first diversion scheme in Metering Level I was based on the amount of overflow queue observed under the no-diversion Metering Level I simulation. The first scheme diverts either all the short trips or sufficient short trips to eliminate the overflow queue at each on-ramp, whichever is smaller. Here a short trip is defined as a trip that starts at a given on-ramp, enters the freeway, and exits at the first downstream off-ramp. For example, in Figure 1, a vehicle on Link 63-64 that is destined to traverse a path 63-64-132-32-33-34-71-72-73-75 would divert to the path 63-64-65-209-180-73-75.

To reflect the diversion on the traffic flow in the network, the following steps were taken:

1. At each on-ramp, determine the original routes of those trips that are destined for the next interchange (referred to as one-interchange trips) and determine the most probable alternative arterial routes.
2. Determine the original routes and alternate routes link by link for each on-ramp.
3. On the basis of the amount of diverted traffic and the identification of the alternate routes, revised turning percentages and O-D assignments were calculated for each affected link.

Second Diversion Scheme in Metering Level I

In order to eliminate overflow queue conditions that remained after the initial diversion, a certain number of trips destined for the second interchange from each on-ramp (two-interchange trips) were diverted to surface streets through an alternate route. The exact number of vehicles to be diverted was based on the overflow queue computation.

Third Diversion Scheme in Metering Level I

A third diversion scheme was devised for Metering Level I in which more two-interchange trips from ramps that still have these types of trips were diverted to reduce the number of stored vehicles at each ramp to short queues relative to the available storage capacity.

The speeds on the freeway tend to fall as more vehicles making short trips are diverted from the metered ramps. This is because the metering rates are held fixed but the short trips (one and two interchanges) are diverted. Thus, a greater percentage of the vehicles that are allowed through the meters are long trips destined downstream of the incident site. Another source for variations in speed is the stochastic variation in the assignment of individual vehicles by the O-D trip distribution. To offset such variations, the demand on the freeway was reduced by reducing the metering rate at one ramp.

Fourth Diversion Scheme in Metering Level I

The results of the previous simulation with a reduced metering rate at one ramp caused only a very minor increase in the average speed on the freeway at the completion of Subinterval 2. This situation occurred in spite of the reduction of 154 vehicles in the 45-min incident period while keeping the diverted vehicles as in the previous simulation. To eliminate the resulting overflow queue on this ramp, 40 two-interchange trips in 45 min were diverted.

Design of Metering Level II: More Restrictive Metering

In this strategy, more restrictive ramp metering was used so that the total hourly demand on the incident link would be further reduced by 400 vehicles compared with the demand in the Level I restrictive metering. This reduction in demand was made to offset the effect of the stochastic variations in the on-ramp origin-destination assignment. The new reduction in demand was made higher than any likely increase in demand on the freeway link with the incident due to these stochastic variations. This is, in fact, what is done in actual systems that use time of day metering plans. A real-time traffic-responsive metering strategy would be able to respond to these stochastic fluctuations and thus, on the average, meter less heavily.

First Diversion Scheme in Metering Level II

All the single-interchange trips originating from the six metered on-ramps were diverted as in the first diversion scheme of Metering Level I.

Second Diversion Scheme in Metering Level II

A sufficient number of two-interchange trips were diverted to eliminate the overflow queues at each metered ramp. However, at one on-ramp, diverting all two-interchange trips was not sufficient to eliminate the overflow queues.

TABLE 1 Summary of Delay and Number of Diverted Vehicles in All Cases

Case	Number of Diverted Trips				Adjusted Delay (Vehicle-Minutes)			Unadjusted Delay
	1-Interch	2-interch	3-Interch	Total	Total System without No Incident Freeway Direction	Surf. Streets Without Ramps & Preceding Links	Freeway Incident Direction	For Ramps and Preceding Links (Veh-Min)
Basic Simulation	0	0	0	0	89837	65992	23395	452
Metering Level I	0	0	0	0	103236	81860	11182.00	10429
1st Diversion	288	0	0	288	90457	68029	14500.00	7824
2nd Diversion	288	106	0	394	85784	65664	13779.00	6038
3rd Diversion	288	174	0	462	83253	64394	14550.00	3918
3rd Diversion *	288	174	0	462	85075	64636	15596.00	4618
4th Diversion	288	214	0	502	80451	63589	11717.00	4663
Metering Level II	0	0	0	0	118376	97622	10137.00	10788
1st Diversion	306	0	0	306	95073	76913	9756.00	8183
2nd Diversion	306	282	0	588	80936	63661	10731.00	5830
3rd Diversion	306	282	87	675	84210	64612	14650.00	4381
Metering Level III	0	0	0	0	88651	63404	19506.00	5841
1st Diversion	82	22	0	104	86579	64339	18918.00	3385

* This third diversion is the same as the preceding one except that less metering was introduced at one ramp

Third Diversion Scheme in Metering Level II

At this ramp, then, a number of three-interchange trips had to be diverted.

Design of Metering Level III: Less Restrictive Metering

This strategy was based on metering rates that did not result in any overflow queues from the ramp meters. It is equivalent to a scenario in which metering rates are increased when the overflow queue is detected by a presence detector at the upstream end of a ramp. There was only one stage of diversion needed in Strategy III. The number of vehicles diverted at one ramp was based on the previously stated requirement that there should be the same number of queued vehicles behind a meter in the final diversion scheme in each level of metering. Table 1 includes a summary of the number of diverted vehicles in the period from 4:15 to 5:00 p.m. by type of trip (i.e., one-interchange, two-interchange, or three-interchange).

ANALYSIS OF RESULTS

The total corridor was divided into the following subsystems:

1. Portion of the freeway in the direction with the incident,
2. Metered on-ramps and their preceding links,
3. Surface street subsystem, and
4. Total system without no-incident direction of the freeway.

The INTRAS MOEs output includes results on a link-by-link basis, which permits separating the MOEs in the subsystems mentioned. All the MOEs are output cumulative at the end of every 15-min period in the 90 min of simulated traffic flow. Delay, as defined in this study, is the difference between the actual travel time that vehicles take to traverse the links and the time vehicles would take to travel the links at the free-flow speed. Thus, the comparison of delay in two separate cases in the same system or subsystem provides a comparison of each metering level/diversion scheme combination.

Analysis of Delay

Total System

The changes in the delay (given as vehicle minutes) in the total system (without the no-incident freeway direction) were evaluated at the end of the 90-min simulation period. The values for total delay were adjusted to reflect the fact that the total number of vehicle miles was not constant between simulation runs. The adjustment was done by factoring all values to reflect the no-metering simulation (this is equivalent to using delay per vehicle mile as the MOE). Table 2 presents the MOEs for the total system including adjusted delay and the changes in the adjusted delay in all cases with and without diversion. Hence, on the basis of delay reduction in the total system, Metering Level III is the best strategy considering metering only without diversion. It is, however, the least effective for alleviating congestion on the freeway.

Freeway Subsystem

Table 3 presents the MOEs of the freeway subsystem. It indicates that the most restrictive Metering Level II is the best strategy for alleviating the effects of the incident. However, Table 3 indicates that delays on the incident direction for various cases of diversions vary within the same ramp metering level because of short trips being diverted and stochastic variability of OD assignments, as discussed previously.

TABLE 2 Summary of MOEs in Total System Without No-Incident Direction on the Freeway

Case	Delay (Veh-Min)	Adjusted Delay (Veh-Min)	Change in Adj. Delay (%)	Travel (Veh-Mile)	Change in Travel (%)	Travel Time (TT) (Veh-Min)	Adjusted TT (Veh-Min)	Change in Adj. TT (%)	Average Speed (mph)	Change in Av.Sp (%)
Basic Simulation	89837	89837	0	110000	0	232031	232031	0	28.44	0
Metering Level I	102771	103236	14.91	109505	-0.45	244227	245331	5.73	26.90	-5.42
1st Diversion	90367	90457	0.69	109890	-0.10	232432	232665	0.27	28.37	-0.27
2nd Diversion	85733	85784	-4.51	109934	-0.06	227619	227756	-1.84	28.98	1.88
3rd Diversion	83026	83253	-7.33	109700	-0.27	224983	225598	-2.77	29.26	2.85
3rd Diversion*	85158	85075	-5.30	110107	0.10	227338	227117	-2.12	29.06	2.17
4th Diversion	80592	80451	-10.45	110193	0.18	223289	222898	-3.94	29.61	4.10
Metering Level II	116902	118376	31.77	108630	-1.25	257404	260650	12.33	25.32	-10.98
1st Diversion	94866	95073	5.83	109760	-0.22	236802	237320	2.28	27.81	-2.23
2nd Diversion	80599	80936	-9.91	109542	-0.42	222429	223359	-3.74	29.55	3.88
3rd Diversion	84447	84210	-6.26	110310	0.28	227344	226705	-2.30	29.11	2.35
Metering Level III	88659	88651	-1.32	110010	0.01	231034	231013	-0.44	28.57	0.44
1st Diversion	86664	86579	-3.63	110108	0.10	228988	228763	-1.41	28.85	1.43

* This third diversion is the same as the preceding one except that less metering was introduced at one ramp

TABLE 3 Summary of MOEs in Freeway Subsystem Without No-Incident Direction on the Freeway

Case	Delay (Veh-Min)	Adjusted Delay (Veh-Min)	Change In Adjusted Delay (%)	Travel (Veh-Miles)	Change in Travel (%)	Travel Time (TT) (Veh-Min)	Adjusted TT (Veh-Min)	Change in Adj. TT (%)	Aver.Speed (mph)	Change in Av.Sp (%)
Basic Simulation	23395	23395	0	46719	0	67502	67502	0	41.53	0
Metering Level I	11198	11182	-52.20	46784	0.14	55146	55069	-18.42	50.9	22.56
1st Diversion	14473	14500	-38.02	46632	-0.19	58137	58245	-13.71	48.13	15.89
2nd Diversion	13690	13779	-41.10	46417	-0.65	57512	57886	-14.25	48.43	16.61
3rd Diversion	14397	14550	-37.81	46227	-1.05	57913	58529	-13.29	47.89	15.31
3rd Diversion *	15559	15596	-33.33	46607	-0.24	59262	59404	-12.00	47.19	13.63
4th Diversion	11616	11717	-49.92	46317	-0.86	54992	55469	-17.83	50.53	21.67
Metering Level II	10063	10137	-56.67	46377	-0.73	53481	53875	-20.19	52.03	25.28
1st Diversion	9712	9756	-58.30	46507	-0.45	53624	53868	-20.20	52.04	25.31
2nd Diversion	10527	10731	-54.13	45830	-1.90	53541	54580	-19.14	51.36	23.67
3rd Diversion	14509	14650	-37.38	46269	-0.96	57795	58357	-13.55	48.03	15.65
Metering Level III	19582	19506	-16.62	46902	0.39	63800	63551	-5.85	44.11	6.21
1st Diversion	19002	18918	-19.14	46927	0.45	63244	62964	-6.72	44.52	7.20

* This third diversion is the same as the preceding one except that less metering was introduced at one ramp

Thus, as far as the reduction in the delay on the freeway (incident direction) is concerned, simulation of the final diversion scheme in Metering Level I with 502 diverted trips and simulation of the second diversion scheme in Metering Level II with 588 diverted trips represent the best cases having almost equal reductions in delay (49.9 percent and 54.1 percent, respectively).

Ramp and Preceding Link Delay

On the basis of the delays on ramps and preceding links (e.g., referring to Figure 1, Link 134-38 is a ramp link and Link 79-134 is a preceding link) presented in Table 1, the increases in delay for the metering cases (compared with the no-metering basic case) were very drastic as expected. On the other hand, when the diversion schemes were invoked, these delays were reduced proportionally to the number of diverted vehicles. In the final cases of diversions in Metering Levels I, II, and III, the reduction in delay was 55.3, 59.4, and 72 percent, respectively, relative to the delay in the no-diversion metering case for each metering level. The maximum encountered average delay per vehicle of 737 sec (approximately 12 min) falls within the acceptable limits of on-ramp delays reported in many experiences.

Surface Street Delay

Table 4 presents the MOEs for the surface street subsystem (not including the links immediately upstream of the meters) for cases with and without diversion. The changes in the cases without diversion for Metering Levels I, II, and III were calculated relative to the delay in the no-metering basic simulation case and were 24.1, 47.9, and 3.9 percent, respectively. The large increases in delay for the two most restrictive levels

TABLE 4 Summary of MOEs on the Surface Street Subsystem Without Ramps and Preceding Links

Case	Delay (Veh-Min)	Adjusted Delay (Veh-Min)	Change in Adjusted Delay (%)	Travel (Veh-Miles)	Change in Travel (%)	Travel Time (TT) (Veh-Min)	Adj. TT (Veh-Min)	Change in Adj. TT (%)	Aver. Speed (mph)	Change in Av.Sp (%)
Basic Simulation	65992	65992	0	62311	0	162363	162363	0	23.03	0
Metering Level I	81144	81860	24.05	61766	-0.87	176981	178543	9.97	20.94	-9.08
1st Diversion	68070	68029	3.09	62349	0.06	164878	164778	1.49	22.69	-1.48
2nd Diversion	66004	65664	-0.50	62634	0.52	162521	161683	-0.42	23.12	0.39
3rd Diversion	64711	64394	-2.42	62618	0.49	161668	160875	-0.92	23.24	0.91
3rd Diversion *	64981	64636	-2.06	62644	0.53	161961	161100	-0.78	23.21	0.78
4th Diversion	64315	63589	-3.64	63022	1.14	162144	160315	-1.26	23.32	1.26
Metering Level II	96051	97622	47.93	61308	-1.61	191503	194636	19.88	19.21	-16.59
1st Diversion	76971	76913	16.55	62358	0.08	173425	173294	6.73	21.57	-6.34
2nd Diversion	64242	63661	-3.53	62880	0.91	161604	160142	-1.37	23.35	1.39
3rd Diversion	65557	64612	-2.09	63222	1.46	163732	161373	-0.61	23.17	0.61
Metering Level III	63236	63404	-3.92	62146	-0.26	159699	160123	-1.38	23.35	1.39
1st Diversion	64277	64339	-2.50	62251	-0.10	160721	160876	-0.92	23.24	0.91

* This third diversion is the same as the preceding one except that less metering was introduced at one ramp

of metering were due to the overflow queues blocking the links feeding the links upstream of the meters.

Table 4 indicates that delay decreased when the various traffic diversion schemes were invoked for the two more restrictive levels of metering. This is because the added delay due to the increase in demand on the surface street network was more than compensated for by the decrease in delay due to the overflow queues.

The MOE space mean speed reflects both the travel miles and travel time. Tables 1 through 4 also present the speed changes for all simulations. Figures 2 through 4 show the results graphically.

Analysis of Rerouted Trips

To complete the evaluation, we must consider the changes in vehicle miles traveled and vehicle minutes of travel for diverted vehicles as compared with the original freeway routes. To accomplish this, the vehicle-minutes and vehicle-miles for each link of each route during Subinterval 2 were extracted from the cumulative values for all diversion schemes. From those data, an average travel time per mile on each such link was calculated for that period and then the actual travel times of trips on the diversion routes were obtained.

The incremental schemes for diverting vehicles permitted the comparison of the alternate routes of the last diverted trips with the original routes in the previous simulation. The total length of all original routes for all diversion schemes is not very different from the total length of all alternate routes (3,071 vehicle-mi versus 3,024 vehicle-mi). However, the total travel time involved in using the original routes, for all diversion schemes, is about twice that of the alternate routes (262 vehicle-hr versus 137 vehicle-hr). This indicates that the diversion schemes are valid according to Wardrop's principal,

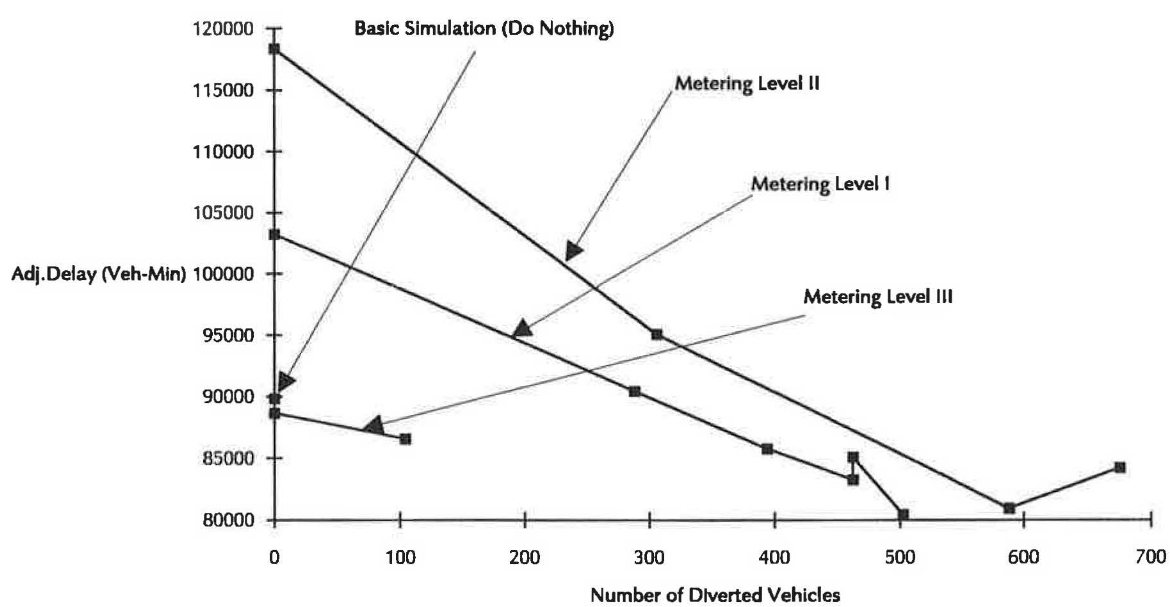

FIGURE 2 Adjusted delay in the total system without no-incident direction on the freeway.

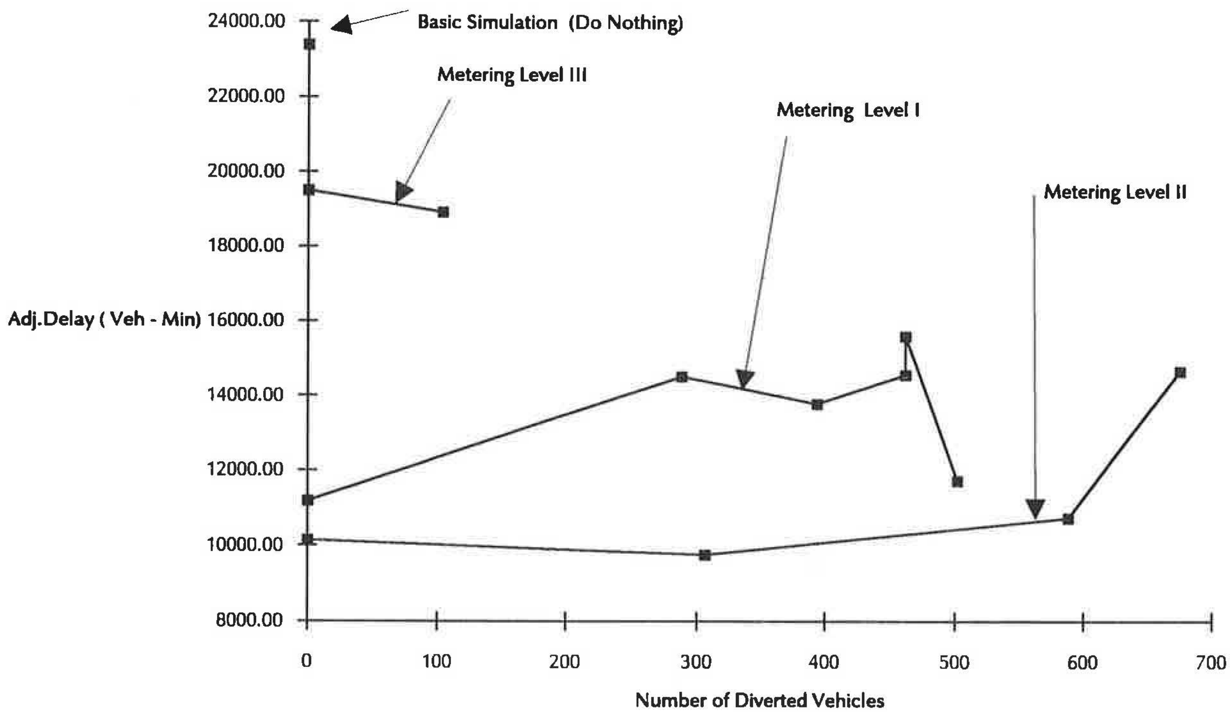

FIGURE 3 Adjusted delay in freeway in the direction of incident only.

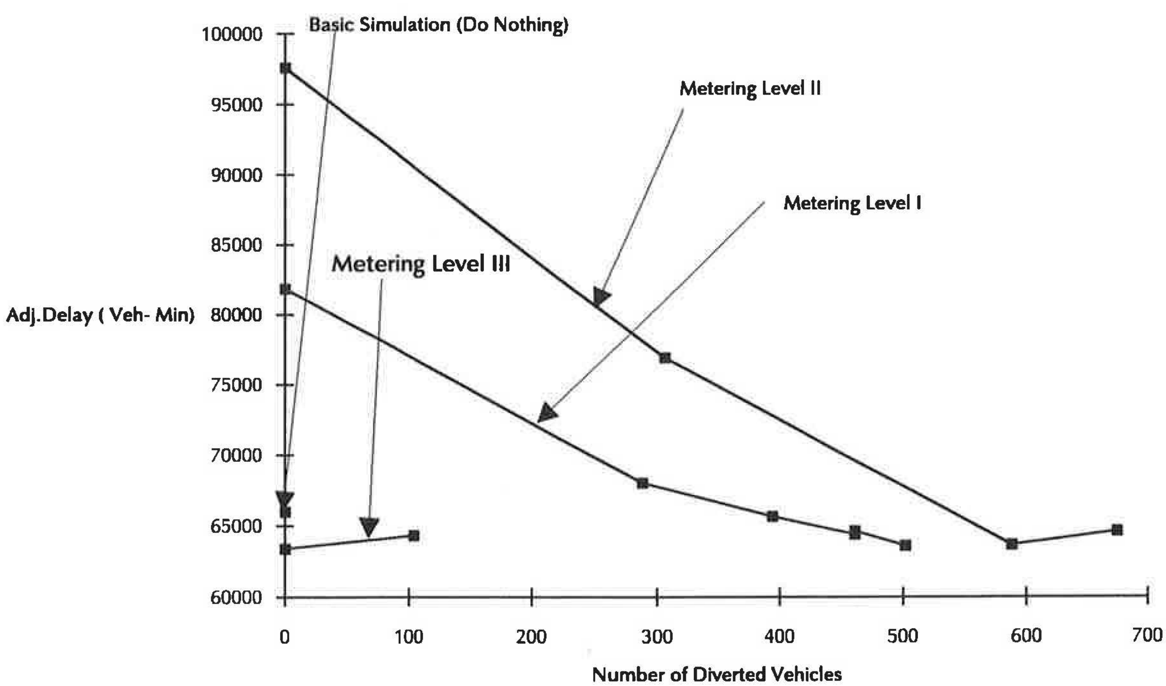

FIGURE 4 Adjusted delay in surface streets without preceding links to metered ramps.

which states that drivers will attempt to use their perceived shortest travel time route.

CONCLUSIONS

The most important conclusions of this study are summarized in this section. The conclusions show that the purpose of the study and its objectives have been achieved.

1. This study demonstrates that, to improve overall network performance by ramp metering, significant diversion from metered ramps is required. This in turn requires that good alternative routes exist. The best results were achieved when all overflow queues behind the meters were alleviated by diverting short trips to alternate routes. However, the improvements were relatively modest compared with some previous results that predict 40 to 50 percent improvements. The previous results were obtained by ignoring the details of the alternate routes, unlike this work, in which these details were included. It is unlikely that even the improvements shown in this study will be obtained in networks with poorer alternate routes (which probably occur in the majority of freeway corridors).
2. Metering Level II with the maximum diversion scheme yielded improvements comparable with those obtained in Metering Level I with the maximum diversion scheme, but it required more vehicles to be diverted to reach the same level of performance. On the other hand, the performance of the freeway was substantially better during Level II than during Level I. In Metering Level III, the improvement in freeway congestion is substantially less than in the other two levels, although no vehicles need be diverted to avoid overflow queues behind the meters. Therefore, this strategy is less effective in reducing freeway congestion.
3. The best case achieved in this study increased the average speed in the total system by 4.1 percent and reduced the total delay by 10.5 percent. This is equivalent to a reduction of 154 vehicle-hr of delay during a 1.5-hr period in which an incident took place for 45 min and closed one lane. Moreover, the significance of this case is that it achieved these total system benefits while addressing the basic direct need of reducing the adverse effects of an incident on the freeway traffic flow in a manner allowing the restrictive Metering Level II. Also, the resulting benefits were achieved by diverting 502 vehicles to alternate routes that took less travel time than they would have for their original routes had they traveled on the freeway after waiting in queues behind the meters. Finally, the users of the surface street subsystem did not incur any significant increase in travel delay because of the diverted vehicles (probably because the diverted flow was very small compared with the existing demand on the surface streets).
4. The INTRAS model was shown to be a powerful tool for analyzing ramp metering and associated traffic diversion. No previous study was able to analyze the alternate surface streets routes to the same level of detail as is available in the INTRAS model.

RECOMMENDATIONS

Following are the major recommendations based on the conclusions and procedures of this study:

1. A capability of assigning alternate routes for diverting vehicles away from metered ramps and automatically adjusting turning fractions and freeway OD matrices would be helpful in performing analyses like those done in this study. This had to be done by hand in this study. Modifying the input headways for metering to tenths of seconds would also help in adjusting metering plans with more precision.
2. Further studies involving ramp metering with diversion are needed to examine the effect of extending the metering period beyond the end of the incident. This would allow faster clearance of the incident on the freeway and would allow one to study the effect of gradually increasing metering rates as the incident clears. Currently, the INTRAS model does not have the capability of changing metering rates within a simulation run, although work is under way to add such a capability.
3. A more refined method is needed to address the fact that vehicles start to divert after a queue has formed behind a meter. In this study, it was assumed that diversion begins immediately after metering begins.
4. A further refinement that should be introduced in similar studies is to consider diverted trips that may reenter the freeway downstream of the incident. This potential for diverting trips was ignored in this study, which only diverted trips that do not return to the freeway.

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