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Authors

Kang, Seungmin

Gillen, David

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Seungmin Kang and David Gillen

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Abstract

This study undertakes an evaluation of the benefits and costs of ramp metering. The primary purpose was to provide empirical information on the value of the introduction and use of this form of ITS technology. Three cases are examined in the analysis. The impact of ramp metering on traffic behavior is simulated based on a cell transmission model and an assumed travel demand on the freeway as well as the ramp. Temporal travel demand change is determined based on the average travel pattern obtained from the I-880 freeway database. Isolated, single traffic responsive ramp metering is assumed. We identify and quantify the benefits and costs based on established assumptions, and finally analyzed economic value of ramp metering. Benefits of ramp metering are derived based on travel time value and fuel consumption and by savings in travel delay. In this study, it turns out that there is a net increase in vehicle emissions as a result of with ramp metering.

The costs of ramp metering are site dependent and a function of planned metering technology. Since this study is not for any specific site, costs are estimated for three cases obtained from conversation with traffic engineers at Caltrans District 4 or literature.

Under the original assumptions regarding fuel economy, time value and travel demand on the freeway and the ramp, investing in ramp metering generates a NPV of $10.44 million. For all three cost scenarios, ramp metering turns out to be worthwhile implementing – the Benefit-Cost ratios exceed 1 in all cases..

To examine the effect of change in some of the assumptions, we conducted sensitivity analysis. Since the original assumptions yield output favorable to ramp metering, we altered the assumptions to reduce the benefits. Specifically we reduce fuel economy but this does not make a significant change in benefits (1.6 % of previous total benefits). Since time saving is the major source of benefits, we reduced the time value. This resulted in a reduction in benefits of 26.5 %, however, ramp metering is still worthwhile implementing based on all three measures of B/C ratio, NPV and IRR. Ramp demand is reduced to 50% of previous demand. This reduction in ramp demand results in a reduction in travel demand such that it is less than capacity for the first four years. Therefore the ramp is not metered and does not generate any benefits until after the forth year once the ramp meter is put in place. As well, freeway demand is reduced to 10% of the previous level. This reduction of freeway demand results in a level of travel demand that is less than capacity for the first five years. Sensitivity analysis for different values of capacity reduction is also conducted. Two different cases of capacity reduction are analyzed: 98% and 99% of normal capacity. As a result of the reduction in capacity, the amount of travel delay reduction resulting from ramp metering is reduced by approximately 64% and 31% respectively. However, ramp metering still is worthwhile implementing.

Keywords

Ramp Metering, Benefit-Cost, ITS, Ramp Metering Technology, Traffic Simulation

Introduction

Traffic congestion occurs when travel demand exceeds capacity. Such congestion is a daily occurrence on much of the urban freeway network. Traffic congestion can generally be classified into two types: recurrent congestion that is routinely expected at predictable locations during specific periods of time, and non-recurrent congestion that arises due to temporary reduction of capacity caused by accidents and incidents (crashes, breakdowns, or other unexpected occurrences).

To alleviate traffic congestion due to recurrent congestion, ramp metering has been applied in numerous cities in the United States as well as throughout the world. Ramp metering aims to limit the number of vehicles entering the freeway from entrance ramps at specific periods of time so that freeway flow can be maintained at or better than a desired service level. Excess demand is forced to wait at the entrance ramp. The intention of ramp metering is, therefore, to maintain uninterrupted, non-congested flow on the freeway as long as possible by transferring delay from the freeway to the entrance ramp. As a result of ramp metering some traffic will divert to alternative routes or perhaps to alternative departure times. It is highly unlikely that any modal diversion would occur.

Various positive effects of ramp metering systems on freeway traffic have been reported based on comparisons of traffic flow operations before and after ramp metering. However, those positive effects reflect only traffic improvements caused by ramp metering systems, and fail to include the costs imposed by ramp metering. Comprehensive economic evaluation has been left unfulfilled in research and practice. This is a goal of this report. We identify benefits and costs of ramp metering, and develop a framework to conduct a benefit-cost analysis of ramp metering, including a simple traffic simulation tool.

This report begins by identifying the key ramp metering technology. This is followed by a literature review of published ramp metering algorithms. Previous practical experience of ramp metering is also reviewed. Benefits and costs of ramp metering are identified based on the previous experience. The traffic model used to simulate freeway traffic behavior is described. Benefit-cost analysis is conducted based on benefits derived from the simulation and costs of ramp metering.

Ramp Metering Technology

A ramp metering system consists of various components. Often these components are elements within the larger freeway management architecture. These components are:

- Ramp Metering Signal and Controller- The signal is typically located to the drivers left, or on both sides of the ramp. Each ramp meter typically has one nearby weatherproof control cabinet which houses the controller, modem(s), and inputs for each loop. A multi-lane ramp meter is served with a single cabinet. The controller is set to a specified algorithm, which controls the ramp metering rate. A widely used controller is the Type 170 Controller developed jointly by the states of New York and California (to be upgraded to the Type 2070 Controller).

- Advance Warning Signage- MUTCD (Manual of Uniform Traffic Control Devices) recommends one or two advance warning signs with flashing beacons indicating that ramp metering is active.
- Check-In Detector- The check-in, or demand detector is located upstream of the ramp metering cordon line. The check-in detector notifies the controller that a vehicle is approaching and activates the green interval. It is common to use two or more demand detectors per lane to avoid situations where a vehicle stopped just upstream of the detector is not recognized by the controller and the ramp meter fails to switch to green.
- Check-out Detector-The check-out, or passage detector is located downstream of the ramp metering cordon line. The check-out detector notifies the controller that a vehicle has passed through the ramp meter and that the signal should be returned to red. In this manner, one vehicle passes per green interval.
- Merge Detector-The merge detector is an optional component which senses the presence of vehicles in the primary merging area of the ramp. To prevent queuing in the primary merging area, the controller holds a red indication if the merge detector indicates a vehicle within this area. This prevents vehicles having to merge onto the freeway from a stopped position, requiring additional acceleration distance on the mainline and disrupting mainline vehicle speeds. This typically occurs when a timid motorist hesitates, impacting subsequent vehicles. In the case of single-entry metering, subsequent green intervals are preempted until the vehicle merges.
- Queue Detector- The queue detector is located on the ramp, upstream of the check-in detector. The queue detector prevents spillover onto the surface street network. Continued actuation of the queue detector with no actuation of the check-in detector indicates that the first queued vehicle has stopped in advance of the check-in detector, and the ramp metering signal should be turned to green to allow this vehicle to proceed. Once ramp queues reach the queue detector and queues begin to spill onto the surface street, the metering rate is reduced or terminated by lengthening the green time and access to the freeway. This can also be accomplished with multiple check-in detectors, as already discussed.
- Mainline Detectors- Mainline detectors are located on the freeway upstream, and downstream of the on-ramp. For isolated ramp metering applications, only the occupancy/flow registered from upstream detectors influences the ramp metering rate if the metering is adaptive (not preset), responding to traffic conditions. For ramp metering systems, data from both upstream and downstream detectors influence the metering rate.

Ramp Metering Algorithms

Local Control

The earliest and simplest applications of ramp control are local control techniques. A ramp-metering rate is computed at each ramp, based on traffic conditions on the adjacent freeway section only. The ramp rate can be either pre-timed or traffic-responsive.

Pre-timed Ramp Control

In the pre-timed ramp metering systems, the ramp signal operates with a constant cycle in accordance with a metering rate prescribed for the particular control period. Ramp rates are fixed and determined based on historical traffic observations, assuming that identical or similar traffic patterns are repeated everyday. The most important advantages of the pre-timed ramp systems are to provide the driver a dependable situation to which he/she can readily adjust and the low costs associated with pre-timed metering. The major disadvantage is that the system can neither respond automatically to significant changes in demand, nor adjust to unusual traffic conditions resulting from incidents.

Traffic-responsive Ramp Control

In contrast to the pre-timed metering control, traffic-responsive metering is directly influenced by the mainline and ramp traffic conditions during the metering period. Metering rates are selected on the basis of real-time measurements of traffic variables indicating the current relation between upstream and downstream capacity. The primary traffic-responsive ramp controls are demand-capacity control and gap acceptance control.

<u>Demand-capacity Control</u>

Demand-capacity control was introduced with the earliest field implementations of responsive ramp control. With this scheme, ramp rates are selected based on a real-time comparison of upstream flow and downstream capacity. The difference between the upstream flow and the downstream capacity is then determined and used as the allowable entrance ramp flow. This ramp flow is expressed as a metering rate to be used during the next control interval.

Metering is initiated: (1) the mainline or ramp flows (or occupancy) exceed pre-specified locally calibrated thresholds or, (2) downstream flow (occupancy) drops below a preset value. The algorithm determines the metering rate locally from input-output capacity considerations as follows (for rates based on flow data):

$$R(t) = C - I(t-1)$$

where: R - number of vehicles allowed to enter in period t
C - Capacity of freeway section
I(t-1) - Upstream flow in period t-1

The upstream flow, I(t-1), is measured by the loop detector and the downstream capacity, C, is a predetermined value.

Since the same flow can be observed in both congestion-free and congested conditions, the use of measured flow, as a determinant of metering decisions is troublesome. As an alternative, speed measurements are used as a metering criterion [Keen et al., 1988]. Downstream occupancy is also used as the indicator of local traffic conditions for local feedback control of ramp metering in models like ALINEA [Papageorgiou et al., 1991].

Traffic-predictive algorithms use "feedback" to determine the ramp metering rate for subsequent periods and anticipate operational problems before they occur. The basic principle behind traffic responsive metering is that real-time data is used to set the metering rate. The term "real-time" actually refers to data retrieved in the previous minute, and not at that instant. One example of such an algorithm is ALINEA (Asservissement LINeaire d'Entree Autroutiere), developed by engineers at the Technical University of Munich. ALINEA is a local-feedback control algorithm that adjusts the metering rate to keep the occupancy downstream of the on-ramp at a pre-specified level, called the occupancy set-point. ALINEA uses occupancy, not flow data, as input. ALINEA incorporates a continuum of metering rates rather than the discrete threshold approach used in other strategies. The feedback control algorithm determines the ramp metering rate as a function of : the desired downstream occupancy; the current downstream occupancy; the downstream occupancy recorded previously; and the ramp metering rate from the previous period:

$$R(k) = R(k-1) + K[O_s - O(k-1)]$$

where:
R(k-1) - number vehicles allowed to enter previous time period
K - constant
O_s - occupancy set-point
O(k-1) downstream occupancy in previous time interval

<u>Gap-acceptance Control</u>
The gap-acceptance control method determines ramp signal in response to the detection of a gap in the merging lane on the freeway. The merge-control concept of ramp metering is intended to enable a maximum number of ramp vehicles to merge safely without causing significant disruptions to freeway traffic. The concept involves maximum utilization of gaps in the traffic stream of the freeway lane into which ramp vehicles are to merge.

These types of ramp metering algorithms were published mainly in the late 1960's and early 1970's [Drew et al., 1966; Wattleworth et al., 1967; Yagoda and Pignataro, 1970; Munjal et al., 1973].

Gap-acceptance control, sets metering rates based on occupancy measurements taken upstream of the ramp during the previous period, usually 1 minute prior. In gap acceptance control, the ramp signals turn green in response to the detection of an available gap in the merging lane on the freeway such that the ramp vehicle has adequate time to accelerate and merge into the gap. In doing so, the strategy must determine the time for the gap to arrive at the ramp and the time it will take the motorist on the ramp to accelerate to freeway speed. Gap acceptance control is intended to enable a maximum number of entrance ramp vehicles to merge safely without causing significant disruption to freeway traffic by inserting vehicles onto the freeway upon detection of an "acceptable" gap.

Gap acceptance control methods assume all drivers aggressiveness are constant (i.e. each driver will accept the same size gap and will accelerate and merge similarly) and that lane changing does not occur between the upstream detector and the ramp. As a result, these methods have been plagued with difficulties resulting from the instability of measured gaps (both size of the gap and the time to arrival at the ramp), the unreliability of acceleration behavior of vehicles, and lane changing effectively closing gaps.

A study undertaken at the Texas Transportation Institute identified the common problems of gap acceptance control strategies to be: (1) more restrictive metering when compared to demand-capacity control; (2) a higher violation rate; and (3) lower travel times from the ramp meter to the merge area, indicating a smoother merging operation. Although a smoother merging operation is achieved, gap acceptance control may result in overly restrictive metering where the bottleneck is "starved" at times. Furthermore, motorist safety is compromised when the controller places ramp vehicles into perceived gaps that have disappeared due to lane changing.

Coordinated Ramp Control

Coordinated ramp metering refers to the application of ramp control to a series of ramps where the interdependency of ramp operations is taken into account. The primary objective of integrated ramp control is to prevent or reduce the occurrence of congestion on the freeway. Therefore, the control of each ramp is based on the demand-capacity considerations for the whole system rather than on the demand-capacity constraint at each individual ramp.

The very first effort at coordinated ramp control consisted of the development of a steady-state optimization problem for a single time slice using linear programming [Wattleworth, 1967]. The objective is to maximize the total input to the system at the ramp meters, which is equivalent to maximizing throughput. The major constraint was to prevent over-saturation of bottlenecks by storing excess demand in queues upstream of the meters. Instead of maximizing total ramp input, some other objective functions were suggested, such as minimizing total excess capacity [Foot, in Wattleworth, 1967], maximizing total vehicle-miles traveled [May, in Wattleworth, 1967], or maximizing the average flow rate of a freeway [Chen and Cruz, 1974].

Unfortunately, solutions to the steady-state ramp control problem never propose what to do once the traffic demands have subsided, and they never take into account the fact that the nature of the peak demands can change even within the peak period. Time-dependent control systems have been developed. A coordinated feedback control algorithm, METLINE has been proposed on the basis of linear quadratic optimization theory [Papageorgiou et al., 1990]. METLINE is a generalization of local control and assumes linear traffic behavior, which is not always the case. Nonlinear, traffic-responsive coordinated ramp metering algorithms have been developed on the basis of optimal control theory, nonlinear optimization and neural networks [Zhang, 1995].

Integrated Ramp Control and Predictive Capability

A ramp meter often diverts freeway trips entering from the ramp to other alternative arterial routes. This diverted traffic may cause congestion on the alternative routes. To achieve system optimal use of traffic facilities including freeway and arterial, recent ramp meter analyses have been made for the development of ramp metering algorithms with diversion. Ramp meter rates are determined by considering travel demand and capacity on the freeway as well as the impact of metering on the arterial adjacent to the freeway [Chin, 1996].

Most current ramp meter algorithms react to, rather than prevent, bottlenecks. A proposed solution involves integrating traffic predictive capabilities into the metering logic. Several such algorithms employ neural networks and fuzzy logic techniques [Taylor and Meldrum, 1995].

Fuzzy set algorithms appear to be well suited to ramp metering because they can utilize inaccurate or imprecise information and they allow a smooth transition between metering rates. A variety of parameters are fed to the algorithm, such as upstream and downstream speed, flow, and occupancy, and the duration of the ramp queue. These variables are transferred to degrees of membership for each fuzzy class (fuzzification), analyzed, and defuzzified.

While it is difficult to compare algorithms evaluated under heterogeneous circumstances, comparative results on the same motorway are available. Recent results suggest that the Fuzzy Set algorithms potentially offer the best performance.

Advanced Control Features

Responsive metering systems present the opportunity to implement advanced meter control techniques. One common feature is a queue over-ride, where once ramp queues threaten to spillback onto arterials the metering rate is increased until the queue dissipates. Sophisticated centralized strategies can also be developed, such as those implemented by Seattle and Denver

In the Denver global system, if a ramp is metered at the most restricted rate or is in queue over ride for an extended duration, the ramp is defined as critical and system coordination is initiated. Upstream ramp rates gradually become more restrictive until the critical condition improves.

Advanced features in Seattle include a volume reduction based on downstream bottlenecks and advanced queues over-ride. Once a downstream, congestion prone section surpasses a preset capacity and begins to store vehicles (i.e. more vehicles enter than leave), a volume reduction strategy is distributed over upstream ramps. A weighting factor determines the fractional reduction at each ramp. Seattle also uses a second queue over-ride, which occurs when loop occupancy near an arterial ramp feeder exceeds a threshold for a specified duration.

Ramp Metering Experience

Ramp metering currently is used on over 2,000 miles of freeways in the United States with over 2,200 ramp meters deployed [ITSA, 1995]. Ramp metering has been applied since the 1960’s in the Chicago, Detroit, and Los Angeles areas. Success of these early applications contributed to the extension of ramp metering systems to 22 additional metropolitan areas in the US, by the early 1990’s [Piotrowicz and Robinson, 1995]. The table below lists most of the ramp metering sites in the US [ITSA, 1995].

Table 1 Ramp Metering Systems in US

Metropolitan Area		Number of Meters	Miles of Meters
Arizona	Phoenix	65	N/A
California	Fresno	15	12
	Los Angeles	808	700
	Orange County	278	258
	Sacramento	19	22
	San Bernardino	51	71
	San Diego	134	126
	San Francisco	96	118
Illinois	Chicago	109	136
Michigan	Detroit	49	32
Minnesota	Minneapolis	367	160
New York	Long Island	75	35
Virginia	Arlington	26	32
Washington	Seattle	54	N/A
Wisconsin	Milwaukee	43	32

Success and benefits of ramp metering have been documented in a number of reports. Benefits attributed to ramp metering in the literature include lowered travel times, increased freeway capacity and throughput, and reduced accident rates, fuel consumption and emissions.

Piotrowicz and Robinson (1995) surveyed eight ramp-metering systems in the US for the Federal Highway Administration. Most of these studies were carried out in the mid-eighties or before. Average highway speed was increased by 35– 56% after ramp metering was installed. An analysis of the INFORM program in Long Island, New York showed that motorists entering at metered ramps also experienced an overall travel time reduction of 13.1 % and an increase in average speed from 23 mph to 28 mph. In addition to similar improvements in speed, freeway flow increased by about 14–62% as a result of ramp metering.

Ramp metering reduces congestion by managing traffic demand, improving the efficiency of merging, and reducing accidents. Efficient merging results in fewer accidents, which typically cause major traffic congestion. Accidents were reduced 27-50% as a result of ramp metering. The following is a summary of ramp metering impacts from six locations in the US [Piotrowicz and Robinson, 1995].

Table 2 Reported Benefits of Ramp Meters

	Speed (mph)		Changes in (%)		
	Before	After	Travel Time	Accidents	Flow
Denver, CO	43	50	- 37	- 50	+ 19
Detroit, MI	N/A	N/A	N/A	- 50	+ 14
Long Island, NY	29	35	- 20	N/A	N/A
Minneapolis, MN	34	46	N/A	- 27	+ 32
Portland, OR	16	41	- 156	- 43	N/A
Seattle, WA	N/A	N/A	- 91	- 39	+ 62

Improved traffic flow, particularly the reduction in stop-and-go congestion, decreases fuel consumption and certain vehicle emissions. Analysis in Portland, Oregon suggests that fuel consumption, including the additional consumption caused by ramp metering, was reduced by 2,040 liters of gasoline per weekday. Peak period air pollutant emissions, including carbon monoxide, hydrocarbons, and nitrogen oxides, were reduced in Minneapolis, Minnesota by just under 2 million kg per year.

Described below are summaries of evaluations of deployed ramp metering systems. There are no uniform or standard evaluation criteria and the measures of effectiveness vary with the system objectives. Nevertheless most systems achieved substantial system wide benefits. While it is reasonable to assume that some difficulties and significant costs were also involved, they were not highlighted in the evaluations. It has been argued that many evaluations fail to fully analyze disbenefits, such as the impacts of diversion onto the surface networks. Most U.S. evaluations are almost a decade or more old. Continuous traffic growth suggests that modern evaluations are needed to conclusively assess ramp meter performance.

Table 3 Evaluations of Deployed Ramp Metering Systems

Location and Implementing Agency	System & Site Description	Results
Austin, Texas		
Texas Department of Transportation	Three meters were installed on ramps along a northbound section of I-35 for operation during the AM peak. The section had two bottlenecks, a lane drop and a high volume ramp (1997).	Metering increased throughput by 7.9% and increased speeds by 60%. The meters were later removed when the section was geometrically improved.
Houston, Texas		
Texas Department of Transportation	Ramp meters along the I-10 Katy Freeway were installed in late 1996, and evaluated in early 1997 vs. the pre-metered conditions.	The total daily estimated travel time saving (before metering vs. metering) was 2,875 vehicle-hours. For an estimated value of time of $12.88 per vehicle hour, these timesavings result in benefits of $37,030 per day. TXDOT estimate these time savings will be realized 150 days of the year.[15]
Denver, Colorado		
Colorado Department of Highways	Initiated in the late 1970s, the Denver metering system started with five ramps on northbound I-25. Geometric improvements to bring acceleration lanes to standard length and improve interchange design were required. The Denver system was subsequently expanded to a centralized system with additional meters	An early evaluation was performed during 1981 and 1982 with promising results. Speeds increased dramatically by 58%, vehicle hours of travel decreased by 37%, vehicle emissions dropped by 24%, and accidents dropped by 5%. In a slip up involving daylight savings time, the ramp controller mistimed and traffic became worse than it had been in years. With metering mainline flows exceeded 2450 vphpl (vehicles per hour per lane) on several occasions. Because it eliminated stop and go traffic on the freeway, the system was an immediate public relations success. Motorists shifted their arrival times to avoid ramp delays, and flows on area arterials increased from 100 to 400 vph, resulting in virtually no degradation of surface street conditions. A later evaluation suggested that central coordination was only beneficial when congested conditions (speeds less than 55 mph) existed. However, when speeds were near 55 mph, coordination was of little benefit.

Detroit, Michigan		
Michigan Department of Transportation	Metering was initiated in 1982 with six ramps on east-bound I-94, with many more ramps added later.	Ramp metering increased speeds by about 8%, even though volumes increased from 5600 vph to 6400 vph. The total number of accidents was reduced by nearly 50% and the number of injury accidents dropped by 71%. The evaluation also showed that significant additional benefits could be achieved by metering inter-freeway connectors to I-94.
Great Britain		
Department of Transport	In response to periods of long congestion on the M6 motorway, an isolated, fixed time ramp meter and VMS were implemented. The system was connected to a central computer for monitoring purposes. The initial system released platoons of up to 8 or 9 vehicles.	Results of the study led to the expansion of metering to other sites. Although congestion continued to occur after installation, significant benefits were achieved. Bottleneck capacity increased by 172 vph (3.2%), which resulted in an estimated 20-minute reduction of the peak period. This resulted in daily savings of 107 vehicle hours, worth 110,000 pounds (1986 value) per year. The total capital outlay was 225,000 pounds (1986 value). Assuming an annual maintenance cost of 10,000 pounds, journey timesavings represented a first year rate of return of 40%. Less than 5% of drivers were diverted to surface streets, although there was a shift towards earlier arrivals. Ramp delays added 1.5 minutes to the average travel time. The system enjoyed the support of the police and motoring organizations, with no adverse public reaction. Metering was less effective during winter months in which lower speeds made it difficult to prevent flow breakdown. With higher speeds during the Summer the system was more effective.
Long Island, New York		
New York Department of Transportation	Sixty ramp meters were installed on the eastbound Long Island Expressway as part of the Information for Motorists project (INFORMS). The evaluation was performed between 1987 and	After the meter installation mainline travel times decreased from 26 to 22 minutes, and the averaged motorist using a metered ramp saved 13% in travel time, Average speeds increased from 29

	1990.	to 35 mph. Maximum throughput showed no conclusive results, with a 7% increase in some areas and none elsewhere. For the AM peak the number of detectors showing a speed less than 30 mph decreased by 50%. The average queue lengths at ramp meters ranged from 1.2 to 3.4 vehicles, representing 0.1% of vehicle hours traveled. As part of a public perception survey 40% of respondents viewed the meters favorably while 40% did not think the meters were a good idea.
Minneapolis / St. Paul, Minnesota		
Minnesota Department of Transportation	Meters were installed in the 1970s as part of the Twin Cities Metropolitan Area Freeway Management System. The first installation, along a section of I-35 E, included several meters initially operated on a fixed time metering scheme, but later upgraded to isolated traffic responsive operation.	After 14 years of operation, peak period speeds remained 16% higher (from 37 to 43 mph) than before metering even though peak period volumes increased 25% over the same period. The average number of peak period accidents decreased by 24% and the peak period accident rate decreased by 38%.
	In 1974 along I-35 W an extensive freeway management system was initiated which included 39 ramp meters (some with HOV bypass), CCTVs, VMS, and Highway Advisory Radio.	After ten years of operation evaluation showed that average peak period speeds increased from 34 to 46 mph while average peak throughput increased by 32%. The number of peak-period accidents declined 27% (from 421 to 308 per year) and the peak period accident rate declined 38%. These results were for the entire management system.

Portland, Oregon		
Oregon Department of Transportation	In 1981 meters were installed along I-5, a major north-south link and important commuter route. The evaluated included sixteen meters in fixed cycle operation.	With metering, average northbound speeds increased from 16 to 41 mph. As pre-metered conditions were less severe in the southbound direction, average speeds increased from 40 to 43 mph. It was estimated that fuel consumption, including that caused by ramp delay, was reduced by 540 gallons per weekday. Improved traffic flow also led to a reduction in rear-end and sideswipe accidents. Overall there was approximately a 43% reduction in peak period accidents.
Seattle, Washington		
Washington Department of Transportation	Beginning in 1981, as part of the FLOW program, WDOT implemented metering on I-5 north of the Seattle CBD. A six year evaluation consisted of seventeen southbound ramps during the AM peak and five northbound during the PM peak along a 6.9 mile test corridor.	Over the study period travel time dropped from 22 minutes before metering to 11.5 minutes after, despite higher volumes (mainline volumes increased over 86% northbound and 62% southbound). The accident rate dropped about 39%, and average-metering delays at each ramp remained at or below three minutes.
Zoetemeer, Netherlands		
Dutch Ministry of Transport	Initiated in 1989, nine ramp meters were in place by 1995. This evaluation focused on the A12 motorway between Utrecht and Hague. The road carried upwards of 110,000 vpd on weekdays, but became congested near Zoetemeer due to lane drops and weaving sections.	For the 11 km study area, the ramp metering system increased bottleneck capacity by 3%. Other positive effects included higher speeds during congested periods (from 46 to 53 kph), and 13% shorter travel times (from 13.8 to 12.0 minutes). Although ramp travel time increased by about 20 seconds, total system wide effects were positive.

source: http://www.path.berkeley.edu/~leap/

Costs and Benefits of Ramp Metering

Costs

Ramp metering has a number of categories of costs associated with it. These include capital and maintenance costs associated with the hardware and installation, user costs and spillovers or externalities in the form of congestion, pollution and safety.[1] Careful consideration of potential costs is required, since many are subtle and not easily quantified.[2]

- Installation and Maintenance Costs: Depending on the ramp metering systems to be implemented, capital and maintenance costs vary according to the level of technology selected and the number of units installed. Depending on existing ramp configuration and the size of the system, capital and maintenance costs can be sizable. Ramp metering systems typically have high costs associated with the communication medium connecting the ramps to the control center.
- Ramp Delay and Spill Back Costs: Due to the ramp metering, a queue may be formed on ramp. Queues that back up onto adjacent surface streets can adversely affect the surface street network.[3]
- Ramp Fuel Consumption and Emissions: Metering forces vehicles on the ramp to stop and go, requiring more fuel and producing more air pollution.

Benefits

In principle ramp metering is designed to reduce aggregate congestion by shortening the duration of congestion and improve overall traffic conditions on the primary facility. There is evidence that metering increases throughput, as many metered highways sustain peak volumes well in excess of 2,100 vph[4] (flows up to 2450 vph have been achieved). By eliminating the stop-and-go behavior associated with congestion, metering can also result in an increase in average travel speed and a reduction in accidents. While diversion is an important metering concern, empirical results suggest no more than 5-10% of vehicles will be diverted. More generally, the benefits can be described as:

[1] The safety spillover may be positive or negative on balance. Ramp metering may reduce the number and severity of accidents on the freeway but it may lead to an increase in the number of accidents or incidents due to spillovers onto arterial roadways.

[2] There is some evidence that metering results in longer trips replacing shorter trips, as those trips taking up critical bottleneck capacity are also likely to use the long uncongested upstream or downstream freeway sections. Such catering to longer trips can have negative feedback effects, encouraging rather than discouraging commutes from further out. Some might regard this stimulation of urban sprawl as a cost of the system. While we recognize it we do not include it in the analysis since it would require a broader network simulation model or general equilibrium model to assess the costs.

[3] It may also be the case that ramp meters result in more efficient use of system capacity: This case occurs when freeways tend to be congested and alternative surface streets have excess capacity. Ramp metering encourages part of traffic to divert from congested freeway to the less utilized surface streets. This diversion of freeway traffic to surface streets helps maintain freeway demand less than capacity, so that higher travel speed and service volumes on the freeway can be achieved.

[4] Vehicles per hour

- Travel Time Saving: If well controlled, metering can significantly increase peak speeds and reduce travel times. While ramp delays may increase, system wide delay reductions can be large.[5]
- Improved Safety: Ramp metering improve safety of the merging operation by limiting the platoon of vehicles on the ramp from entering the freeway. Also, ramp metering helps freeway flow smooth and prevents stop-and-go conditions, freeway traffic becomes safer through the reduced variance in speed distribution.
- Reduction of Fuel Consumption and Vehicle Emissions: Smoother flow on the freeway by preventing the occurrence of bottlenecks through ramp metering can lead to substantial reduction in fuel consumption and air pollutant emissions.

It is difficult to measure all of aforementioned costs and benefits. In this study, installation and maintenance costs, ramp delay and emissions on ramp are included as cost factors while travel time saving, reduction of fuel consumption and emission on freeway are taken into account as benefit factors.

The application of benefit-cost analysis to this investment focuses on the principle of obtaining net improvements in economic efficiency. But the process of the implementation can be of significant importance. Within the process component are issues of equity and public support. Because ramp metering favors through traffic, metering benefits longer trips at the expense of "local" motorists. Trips may be diverted to local surface streets, and residents close to the CBD may be deprived of access given to suburban dwellers. In Milwaukee, for example, where equity proved to be a delicate subject, metering rates were adjusted so that delay to the average motorist was the same on close-in ramps and on outlying ramps.

A second issue that can effect the success of installations is public opposition. In addition to physical requirements of the ramp, the feasibility of implementing ramp-metering control is dependent on public acceptance of ramp metering as a strategy to improve the overall productivity of the transportation system.

Traffic Simulation

Traffic Simulation Model

Mathematical models of freeway traffic flow are essential to evaluate ramp-metering strategies. The “cell transmission model” developed by Daganzo (1993) is adapted to simulate freeway traffic behavior for this study. The cell transmission model is a simple but fairly accurate traffic model to predict traffic’s evolution over time and space, including transient phenomena such as the building, propagation and dissipation of queues. The cell transmission model assumes a relationship between traffic flow (q) and density (k) as shown in Figure 1. The relationship can also be expressed as:

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[5] Saving travel time for freeway travelers is the main objective but evaluating the benefits of the ramp meter cannot ignore the time costs imposed on others in the system. In evaluation the key is defining the extent of the system.

$$q = \min\{uk, q_{\max}, w(k_j - k)\}, \quad \text{for } 0 \le k \le k_j$$

where u is free flow speed, q_{max} is maximum flow rate, w is wave speed with which disturbances propagate backward when traffic congested (the backward wave speed), and k_j is maximum density. The cell transmission model approximates traffic movement based on hydrodynamic theory by a set of difference equations. Unlike other traffic models such as Lighthill and Witham (1955) and Richards (1956), the cell transmission model updates current conditions depending on the occupancy of the section receiving the flow as well as the upstream occupancy. The dependence of the downstream occupancy avoids diverged and unreasonable results [Daganzo, 1993].

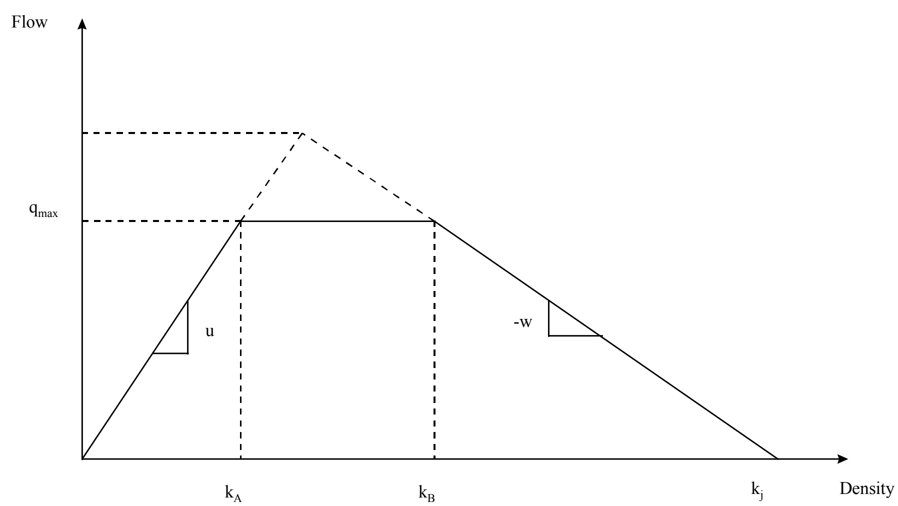

Figure 1 Assumed flow-density relationship

The cell transmission model divides a single road into homogeneous cells, numbered consecutively starting with the upstream end of the road from j to J. Each cell is assumed to have equal distance traveled in light traffic by a typical vehicle in one clock tick τ. Length of the cell is product of speed at light traffic and the size of one clock tick. For instance, if speed at light traffic is 60 mph (88 fps) and size of the time tick τ is 4 second, cell length becomes 352 ft (= 4 sec x 88 fps).

Under light traffic, all the vehicles in a cell can advance to the next with each tick. The vehicle advance can be represented by a recursion where the cell occupancy at time $k+1$ equals its occupancy at time k, plus the inflow and minus the outflow as shown:

$$n_j(k+1) = n_j(k) + y_j(k) - y_{j+1}(k)$$

where $n_j(k)$ is the number of vehicles in cell j at time k and $y_j(k)$ is the inflow to cell j defined as:

$$y_j(k) = \min\{n_{j-1}(k), Q_j(k), d\lfloor N_j(k) - n_j(k) \rfloor\}$$

where $Q_j(k)$ is the maximum number of vehicles that can flow into cell j when the clock advances from k to $k+1$, $N_j(k)$ is the maximum number of vehicles that can be present in cell j at time k, and d is a coefficient to determine speed of backward wave when queues form. $Q_j(k)$ is governed by capacity of the cell j at time k while $N_j(k)$ is by maximum density of the cell. $Q_j(k)$ and $N_j(k)$ are used to incorporate queuing. To enhance accuracy of the approximation, d is defined as [Daganzo, 1993]:

$$d = \begin{cases} 1, \text{ if } n_{j\text{-}1}(k) \le Q_j(k) \\ w/u, \text{ if } n_{j\text{-}1}(k) \le Q_j(k) \end{cases}$$

Boundary conditions can be specified by means of source and sink cells. The sink cell is a destination cell for all exiting traffic, and should have infinite density and an appropriate capacity. The source cell can be divided into two: actual source and gate. The actual source cell has infinite number of vehicles and sends vehicles to an empty “gate”. The gate cell is used to control link input flow for each time interval by setting its inflow capacity equal to the desired link inflow.

The total number of vehicles to have left cell j is the addition of $y_{j+1}(k)$ across time k. If the number of vehicles to have left cell j is equal to the number to have entered, then the added quantity represents the number of vehicles to have flowed through cell j. Therefore, the cell delay j can be computed as:

$$\sum_{k=1}^{K} \left(n_j(k) - y_{j+1}(k) \right)$$

Travel delay change by ramp metering is computed based on the delay equation above.

To simulate effect of entering vehicles to freeway through on-ramp, adaptations are made at the merge cell and downstream of it. Possible condition at the merge is assumed to be either forward or backward moving. Forward moving condition occurs when sum of inflow from freeway and on-ramp is less than capacity of the merge while backward moving happens when the added travel demand is higher than capacity. When backward-moving-queues form due to the traffic merge, it is often observed that capacity of downstream of the merge is decreased [Hurdle and Datta, 1983; Banks, 1990 and 1991]. Specifically, 3% decrease for flow averaged across all lanes is observed from bottlenecks in San Diego, California [Banks, 1991]. For this study, it is assumed that capacity of downstream of the merge is reduced by 3% of normal capacity when the added travel demand is higher than capacity of the merge cell.

When ramp metering is not implement and the sum of inflow from freeway and on-ramp is higher than capacity, entering rates of traffic to the merge cell from freeway and on-ramp are determined by the rate of travel demand. For instance, capacity of the merge cell is 8 vehicles per time tick t, and travel demand on freeway and on-ramp during the time t becomes 7 and 3 vehicles respectively. The added travel demand (10 vehicles) is higher than capacity (8 vehicles). Since freeway travel demand is 70% of the added demand, 70% of 8 vehicles from freeway cell is allowed to advance to the next cell while 30% from on-ramp. The difference between travel demand and capacity (2 vehicles) is queued on freeway cell and on-ramp: 70% of the queue (1.4) is allotted to freeway while 30 %(0.6) is to on-ramp. Capacity of downstream cell of the merge cell is reduced to 97 % of its capacity at light traffic while queues are present at it.

Travel Demand

This study is not about an economic analysis of ramp metering system that plans to be implemented at a certain location. Therefore, necessary information is not available but needs to be assumed. To obtain typical travel pattern on freeway and on-ramp during peak hours, traffic data collected from the I-880 freeway, Alameda, California in 1993 are utilized. The I-880 freeway database has been made available by the freeway service patrol (FSP) evaluation project conducted as part of the PATH (Partners for Advanced Transit and Highways) research [Skabardonis et al., 1995]. Specifically, traffic observed between exits of SR-92 and Tennyson is used. Traffic is aggregated in 15 minutes interval. Traffic observed during 24 weekdays between February 16 to March 19 is averaged. Since FSP database is made based on 1993 traffic, update to present year 1999 is necessary. To update travel demand, constant annual increase rates of 1.5% and 3% are applied for freeway traffic and on-ramp respectively. These rate are assumed, based on the rate used in Gillen et al., (1999) for the benefit-cost analysis of electronic toll collection. In the study, 3% of annual increase rate is assumed for daily traffic. Since this study deals with congested traffic during peak hours, and the annual increase rate at peak hours is often observed to be less than that of daily traffic, less annual increase rate is applied for freeway travel demand (1.5%). However, this study is to investigate effect of ramp traffic to freeway. Therefore, 3% of annual increase rate is applied for ramp demand. The average on-ramp demand is rather low, so we increase it so that the added demand of freeway and on-ramp is close to capacity. Table 3 illustrates travel demand of base year (1999) used for benefit-cost analysis of ramp metering. The 15 minutes average travel demand is assumed to occur at the end of time period (e.g., flow rate at 6:00 AM is 1,006 vph , that at 6:15 AM is 1,155 vph, etc.). Travel demand between ends of two consecutive periods is obtained by interpolating travel demand at the two ends as shown:

$$TD_{t_x} = TD_{t_j} + \frac{TD_{t_{j+1}} - TD_{t_j}}{t_{j+1} - t_j}(t_x - t_j), \qquad t_j \le t_x \le t_{j+1}$$

where TD_{t_x} is travel demand at time t_x, and t_j is time at the end of *j*th period. Figure 2 illustrates variation of the travel demand on freeway and on-ramp.

Ramp Metering System

This study assumes a local, single-entry traffic-responsive ramp metering system. The ramp rate is determined based on local traffic conditions and is updated on the basis of real-time measurements of traffic variables. Specifically, the ramp starts to be metered at the instant the sum of inflow from the freeway and the on-ramp becomes greater than the capacity of the cell downstream of the merge. This rate is recalculated for a pre-selected short time instant (every 4 seconds for this study). The rate is determined based on the difference between upstream freeway flow and the capacity of the cell downstream of the merge. Also, the ramp is assumed to have a single lane and to hold 40 vehicles.[6] When ramp queue is greater than or equal to 40 vehicles, ramp rate is determined to maintain ramp queue less than or equal to the maximum ramp queue 40 vehicles, not as the difference between upstream freeway flow and capacity of the cell downstream of the merge.

Summary of Assumptions

All of assumptions associated with traffic simulation and ramp metering established in this study for traffic simulation include:

- 3-lane freeway and 1-lane ramp are assumed.
- Length of section upstream of on-ramp merge is 1 mile.
- 4 second time tick is used because this is the practical minimum time required a single vehicle to proceed past the ramp [ITE, 1985]. Ramp rate is therefore, updated every 4 second.
- The cell transmission model requires values for four parameter q_{max}, u, w and k_j . This study assumes that q_{max} = 1800 vph, u = 60 mph, w = 15 mph and k_j = 210 vpm. Given these four parameter, we can derive k_A = 30 vpm and k_B = 90 vpm. Figure 3 displays flow-density relationship used for this study.
- Local, single-entry traffic responsive ramp metering system is assumed.
- Maximum queue of the on-ramp is 40 vehicles.
- Ramp is metered if density of the merge cell is equal to or greater than 30 vpm. However, if ramp queue length is bigger than 40 vehicles, regardless of current density of merge cell the extra queue on ramp (i.e., queue length minus 40) is permitted to advance to freeway. This advancement of ramp vehicles to freeway at congested traffic may limit benefit of ramp metering.
- Lifetime of the ramp is assumed to be 10 years.
- Travel demand in the base year (1999) is listed in the table below:

[6] These are assumptions of the model and can be altered to suite local or desired conditions.

Table 3 Assumed base year travel demand in the morning peak

Time Period	Freeway (vph)	On-ramp (vph)
05:45 – 06:00	1,006	218
06:00 – 06:15	1,155	338
06:15 – 06:30	1,340	386
06:30 – 06:45	1,421	463
06:45 – 07:00	1,458	383
07:00 – 07:15	1,499	469
07:15 – 07:30	1,569	707
07:30 – 07:45	1,549	753
07:45 – 08:00	1,508	591
08:00 – 08:15	1,472	563
08:15 – 08:30	1,438	556
08:30 – 08:45	1,376	443
08:45 – 09:00	1,363	353
09:00 – 09:15	1,317	340
09:15 – 09:30	1,305	312
09:30 – 09:45	1,278	353
09:45 – 10:00	1,205	351

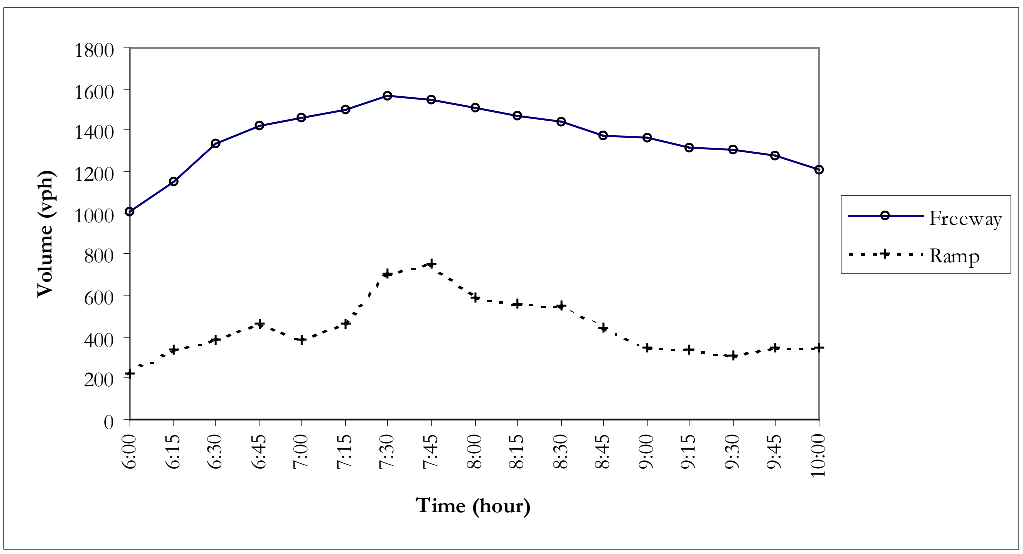

Figure 2 Variation of Travel Demand

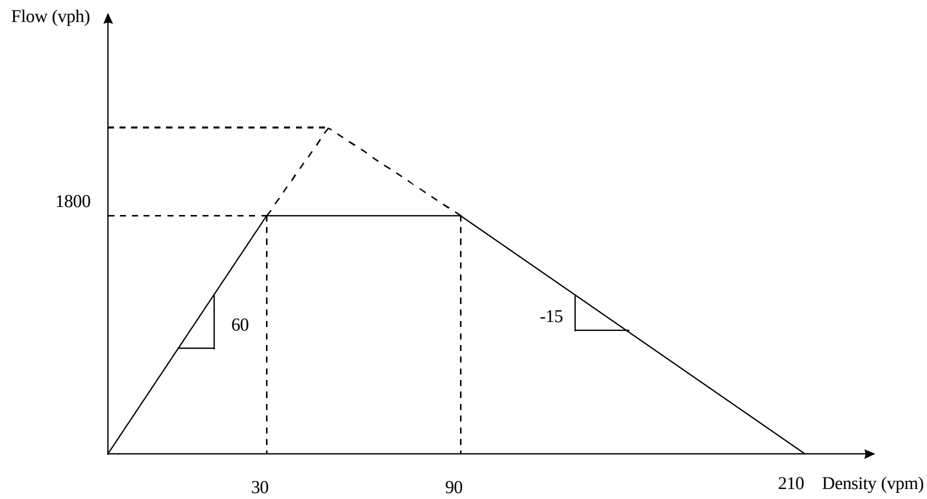

Figure 3 Flow-density relationship used for this study

Temporal Variation of Travel Demand

The period of time travel demand becomes higher than the capacity of the merge cell on freeway at light traffic, and the magnitude of excess demand over the capacity are calculated, based on the assumed base year travel demand in Table 3, constant annual increase rate (1.5 % per year for freeway and 3 % per year for on-ramp), and 3-lane freeway section with capacity of 1800 vehicle/hour/lane. Table 4 shows the period of time travel demand is higher than capacity, and excess magnitude of the demand. In the first year after base year, travel demand is 31 vehicles more than capacity for about 23 minutes. As year passes, travel demand gets higher than capacity earlier than before, and the period of excess demand increases. This is because travel demand increases positive constant rate while capacity remains unchanged.

Table 4 Period and Magnitude of Demand Excess

Year[1)]	Begin[2)] (sec)	End[3)] (sec)	Duration (sec)	Excess[4)] (veh)	Excess[5)] (vph)
1	26,820	28,212	1,392	31	80
2	26,644	28,488	1,844	73	143
3	26,476	28,760	2,284	127	200
4	26,308	29,240	2,932	195	239
5	26,144	29,800	3,656	282	278
6	25,840	30,488	4,648	392	304
7	25,512	30,824	5,312	526	356
8	25,044	31,336	6,292	677	387
9	24,156	31,288	7,132	863	436
10	23,948	31,508	7,560	1,063	506

Note: 1) Year after base year.
2) Time travel demand at merge cell starts higher than capacity in second since midnight.
3) Time travel demand at merge cell returns to below capacity in second since midnight.
4) Total number of vehicles exceeding capacity
5) Hourly rate of vehicles exceeding capacity

Effect of demand excess on freeway and ramp is estimated by the cell transmission model and is summarized in Table 5. As expected, the duration of the queue is longer than the demand excess period. Ramp metering delays the occurrence of the formation of a queue, and shortens its existence and length by limiting vehicle access to the freeway from the ramp. In the first year, when vehicles freely pass the ramp, but a queue starts to occur at second 26,820 lasting until second 30,872. The queue exists for 4,052 seconds and spreads at maximum 1,408 ft backward from the merge cell. However, when ramp is metered, there is no queue on the freeway for the entire simulation period. This is because the excess demand (31 vehicles) is smaller than maximum ramp queue length (40 vehicles), and therefore, capacity reduction does not occur at downstream cell of the merge cell. However, as the year passes and demand increases, excess demand increases and exceeds the maximum ramp queue. As a result a queue starts to form on the freeway with ramp metering.

Note that from the fourth (fifth) year, the maximum queue spreads back to the "gate cell" which is 1 mile back from the merge cell without metering (with metering). Also, from the seventh year, the queue never dissipates until the end of simulation period.

Table 5 Estimates of Queues on Freeway and Ramp

Year	Without Metering					With Metering				
	Begin[1] (sec)	End[2] (sec)	Duration[3] (sec)	F-q[4] (ft)	R_q[5] (veh)	Begin[1] (sec)	End[2] (sec)	Duration[3] (sec)	F-q[4] (ft)	R_q[5] (veh)
1	26,820	30,872	4,052	1,408	5.12	-	-	-	-	32.2
2	26,644	31,776	5,132	3,168	5.09	27,564	31,180	3,616	352	40.0
3	26,476	32,668	6,192	4,928	5.01	27,240	32,212	4,972	1,408	40.0
4	26,308	33,604	7,296	Gate	4.78	27,040	33,212	6,172	3,168	40.0
5	26,144	34,648	8,504	Gate	4.50	26,868	34,260	7,392	Gate	40.0
6	25,840	35,848	10,008	Gate	4.14	26,688	35,480	8,792	Gate	40.0
7	25,512	Never	N/A	Gate	3.87	26,472	Never	N/A	Gate	40.0
8	25,044	Never	N/A	Gate	4.04	26,208	Never	N/A	Gate	40.0
9	24,156	Never	N/A	Gate	4.23	25,640	Never	N/A	Gate	40.0
10	23,948	Never	N/A	Gate	4.42	24,996	Never	N/A	Gate	40.0

Note: 1) Time queue starts to form.
2) Time queue dissipates.
3) Duration of queue existence.
4) Maximum queue on freeway.
5) Maximum queue on ramp.

Estimate of Benefits

Travel Delay Saving

Travel delay saved by local, single entry traffic responsive ramp metering is estimated by the cell transmission traffic simulation model based on the aforementioned assumptions of travel demand and geometry. The estimates of travel delay are summarized in Table 6. As excess demand grows, ramp metering appears to save more total travel time. Average travel time saved in the first year (12.1 second per vehicle) is higher than that in next three years.

This is because travel demand in the first year is not high enough to havea ramp queue longer than capacity (40 vehicles). Therefore, the free flow condition is maintained for the entire simulation period on freeway without occurrence of bottlenecks due to freeway access from the on-ramp. As demand grows, the ramp starts to be metered earlier and more vehicles need to be stored on the ramp (see Table 5). However, due to the limitation of the ramp queue capacity, freeway access from the ramp cannot be stopped when the ramp queue reaches its maximum, and freeway traffic becomes congested with less capacity (97 % of it at free flow). In other words, the rate of ramp delay increase becomes higher than that of freeway delay saving from the second to the forth year (see the growth of ramp delay in Table 6). Beginning in the fifth year the effect of ramp delay increase becomes less and average travel time saving grows through to the ninth year. In the last year, freeway demand becomes close to or greater than capacity for some periods (1,820 vph at 7:15 AM and 1,796 vph at 7:30 AM). Due to the high freeway demand, freeway traffic becomes congested regardless of the magnitude of the ramp travel demand, and ramp metering cannot save as much travel time as before.

Table 6 Total Vehicle-hours and Travel Delay at Morning Peak

Year	Without Metering		With Metering		Change			
	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Net Change (veh-hr)	Average (sec/veh)[1)]
1	391.7	2.6	320.0	11.6	71.7	-9.0	62.7	12.0
2	480.3	3.2	385.2	45.7	95.1	-42.5	52.7	10.0
3	609.0	3.8	498.6	59.3	110.4	-55.5	54.9	10.2
4	788.0	4.4	657.2	72.3	130.8	-67.9	62.9	11.5
5	1,028.6	5.0	874.7	85.8	153.9	-80.8	73.1	13.2
6	1,371.4	5.8	1,175.0	101.4	196.5	-95.6	100.9	17.9
7	1,797.1	6.3	1,574.2	109.1	222.9	-102.9	120.0	20.9
8	2,274.4	6.7	2,017.8	112.6	256.7	-105.9	150.8	25.8
9	2,900.0	7.5	2,580.3	121.5	319.7	-113.9	205.8	34.7
10	3,462.8	7.9	3,192.8	127.1	270.0	-119.1	150.9	25.0

Note: 1) Net travel delay change divided by total travel demand for the entire simulation period.

The travel pattern in the afternoon peak is assumed to be same as that at morning peak.[7] To compute the daily travel delay reduction, therefore, travel delay reduction at morning peak is doubled. Annual delay reduction is calculated by multiplying daily delay reduction by the number of weekdays (261 weekdays = 365 days/year – 2 x 52 weekends/year). Table 7 shows the estimates of annual travel delay change, i.e., travel delay without ramp metering minus that with ramp metering. The estimates of annual travel delay reduction show the same pattern as travel delay at morning peak, by assumption of the same pattern of traffic demand.

[7] This is not essential and can be modeled to reflect local conditions.

Table 7 Annual Travel Delay Reduction (veh-hr)

Year	Freeway	Ramp	Total
1	37,416	-4,712	32,704
2	49,661	-22,169	27,492
3	57,631	-28,993	28,638
4	68,275	-35,454	32,821
5	80,337	-42,159	38,178
6	102,550	-49,890	52,660
7	116,330	-53,700	62,630
8	133,981	-55,258	78,724
9	166,902	-59,480	107,421
10	140,950	-62,183	78,767

Fuel Consumption Saving

The reduction in fuel use is the difference between fuel consumption that vehicles would have without ramp metering and that with ramp metering. Specific assumptions for the estimation of fuel savings include:

- Average travel speed is 60 mph.
- Average fuel consumption is 25 mile per gallon.
- Cost per gallon is $1.10 in FY 95 dollars.

To calculate fuel cost saving, the average hourly fuel consumption is first computed by dividing average travel speed by average fuel consumption, which equals to 2.4 gallons per hour, based on the above assumptions. Fuel cost saving is then estimated by multiplying total vehicle timesaving by hourly gasoline consumption and the unit price of gasoline. Table 8 shows the estimates of fuel reduction cost.

Table 8 Annual Fuel Consumption Reduction

Year	Delay Saving (veh-hr)	Hourly Fuel Consumption (gallon)	Fuel Saving (gallon)	Unit Price ($/gallon)	Value of Fuel Saving (FY95$)
1	32,704	2.4	78,489	1.1	86,338
2	27,492	2.4	65,980	1.1	72,578
3	28,638	2.4	68,732	1.1	75,605
4	32,821	2.4	78,770	1.1	86,647
5	38,178	2.4	91,628	1.1	100,791
6	52,660	2.4	126,384	1.1	139,022
7	62,630	2.4	150,312	1.1	165,344
8	78,724	2.4	188,937	1.1	207,830
9	107,421	2.4	257,811	1.1	283,592
10	78,767	2.4	189,042	1.1	207,946

Passenger Travel Time Saving

Passenger timesaving is the major source of benefits from ramp metering. Timesaving is calculated by multiplying the total delay saving by vehicle occupancy (VOC) weighting factor and is monetized using an assumed value of time savings. We use the factor calculated based on two following assumptions [Gillen et al., 1999]:

- The vehicle split is considered to be 94.76% for automobiles, 5.11% for trucks, and 0.13% for buses.
- Average vehicle occupancy is assumed to be 1.8 for automobiles, 1.1 for trucks, and 20 for buses.
- The VOC weights are computed as:

$VOC_{auto} = 0.9476 \times 1.8 = 1.70568$
$VOC_{truck} = 0.0511 \times 1.1 = 0.05621$
$VOC_{bus} = 0.0013 \times 20 = 0.026$

The value of passenger time saving is the product of total delay saving and a unit value of time, usually measured by dollars per hour. The unit value used in Gillen et al, (1999) is adopted for this study: $12.75 per hour for automobiles and buses, and $33.41 per hour for trucks. Therefore, the factor of time value (weight to transfer travel time saving to value of passenger time saving) can be computed as:

$$\text{Weight} = 12.75 \times VOC_{auto} + 33.41 \times VOC_{truck} + 12.75 \times VOC_{bus} = 23.96$$

The estimates of passenger travel timesaving are displayed in Table 9.

Table 9 Annual Passenger Timesaving

Year	Delay Saving (veh-hr)	Factor of Time Value (FY95$)	Value of Time (FY95$)
1	32,704	23.96	783,485
2	27,492	23.96	658,618
3	28,638	23.96	686,083
4	32,821	23.96	786,286
5	38,178	23.96	914,632
6	52,660	23.96	1,261,569
7	62,630	23.96	1,500,423
8	78,724	23.96	1,885,974
9	107,421	23.96	2,573,482
10	78,767	23.96	1,887,023

Vehicle Emission Change

Ramp metering may reduce emissions by maintaining free-flow traffic and saving travel delay. On the other hand, it may cause an increase in emissions on the ramp by limiting vehicles entering to freeway. Therefore, vehicle emission change by ramp metering includes cutbacks by maintaining travel speed at light traffic and increase due to waiting at on-ramp. Pollutants used in this study include Hydrocarbons (HC), Carbon Monoxide (CO) and Oxides of Nitrogen (NOx). Emission amount at travel is calculated based on emission rates by travel speed. This study uses emission factors produced by EMFAC7G (**Em**ission **FAC**tor), a computer model for estimating on-road motor vehicle emission factors for the state's multitude of on-road cars, trucks and buses [California Air Service Board, ?]. The EMFAC7G model produces emission factors whose magnitudes are function of various factors including calendar years, seasons, processes, pollutants, vehicle class/technologies, speeds and temperature. This study uses emission factors produced with calendar year 2000 and 75 degrees temperature. Autos and trucks are assumed to be catalyst gasoline vehicles while buses are assumed to be diesel vehicles. Factors for light duty autos by EMFAC7G are used for automobiles, those for trucks are for light heavy trucks, and those for buses are for urban buses. Emission factors for HC are converted from those for Reactive Organic Gas (ROG) using conversion factor (1.140641248) as suggested in California Air Service Board (?). The factors by speed are summarized in Appendix A. Travel speed of each cell at time k is estimated, based on the assumed flow-density relationship in Figure 3. Vehicle emissions of freeway traffic at time k are calculated by multiplying the emission factors by the estimated travel speed by number of vehicles traveling in the cell. Total magnitude of emissions is obtained by adding vehicle emission on freeway across cell j and time k.

To compute emission rates at waiting, an idle emission rate is adopted that is used in Gillen et al., (1999). Table 10 shows emission rates at idling.

Table 10 Emission Rates of All Vehicles

	Pollutant		
	HC	CO	NOx
Idle Emission Rates (grams/minute)	0.15	2.5	N/A

Vehicle emissions of ramp traffic at time k are calculated by multiplying the emission rate by the number of vehicles waiting on the ramp. The total magnitude of emissions of ramp traffic is obtained by adding ramp emission across cell j and time k.

The cost of emissions can be computed by multiplying the per unit cost of a pollutant by its amount. This study uses average costs of health damage provided by Small and Kazimi (1995) as in Gillen et al., (1999). Table 11 displays unit cost by pollutant.

Table 11 Unit Costs by Pollutant

	Pollutant		
	HC	CO	NOx
Unit Cost ($/kg)	1.28	0.0063	1.28

The estimates of the annual value of emission reduction on the freeway and the increase on the ramp are summarized in Table 12. Ramp metering reduces emissions of HC and CO on the freeway by maintaining faster speed rather than free pass. However, ramp metering increases emissions of NOx. This is because emission factors of NOx at free speed (60 mph) are higher than those at lower speed (see Appendix). As travel demand grows, maximum ramp queue is reached sooner and ramp metering cannot maintain free-flow speed on freeway.

Table 12 Estimates of Vehicle Emissions

Year	Emission Change from Freeway (kg)			Emission Change from Ramp (kg)		Value of Emission Change (FY95$)			
	HC	CO	NOx	HC	CO	HC	CO	NOx	Total
1	107	1,197	-291	-42	-353	83	5	-372	-284
2	140	1,651	-377	-200	-1,663	-76	0	-482	-558
3	165	1,963	-442	-261	-2,174	-122	-1	-566	-689
4	58	261	-444	-319	-2,659	-334	-15	-568	-917
5	70	633	-302	-379	-3,162	-396	-16	-387	-799
6	74	706	-297	-449	-3,742	-480	-19	-380	-879
7	40	310	-231	-483	-4,028	-567	-23	-296	-886
8	43	354	-221	-497	-4,144	-582	-24	-283	-888
9	62	499	-315	-535	-4,461	-606	-25	-403	-1,034
10	50	376	-273	-560	-4,664	-652	-27	-349	-1,028

Emission reductions by ramp metering is, therefore, decreased. Starting from the forth year, emission reduction on freeway becomes lower than that at the first three years. On the contrary, waiting at the ramp due to ramp metering results in consistent, high emissions of HC and CO. Due to the high emission at ramp, net value of emission change is negative. In summary, ramp metering reduces emissions on freeway and increases those at ramp, and as ramp queue increases, ramp metering appears to increase emissions.

Estimate of Costs

The costing elements of ramp metering include metered ramp construction, metered ramps with signals, and operation and maintenance.

- Metered ramp construction: This item covers the construction cost associated with improving on-ramps to support ramp metering. Included are roadwork, irrigation and drainage, and signing and striping.
- Metered ramps with signals: This item covers the detection and control elements associated with improving on-ramps to support ramp metering. The metering detection consists of ramp closure, installation and material for loop detectors, power and the controller assembly. The control elements are ramp metering signals.
- Operation and maintenance: This item includes costs associated with operation of ramp metering such as electricity, and maintenance to keep ramps in good shape.

Ramp metering cost can vary by location and required function. Since this study is not for any specific location, we assume ramp-metering costs based on data obtained from Caltrans as well as information in the literature. From the literature and conversations with traffic engineers in Caltrans District 4, we have three different cases of ramp metering costs.

Table 13 Unit Cost of Ramp Metering ($1000)

	Case 1[1)]	Case 2[2)]	Case 3[3)]
Construction Cost	750	300	113
Annual Maintenance Cost	75	30	2.2

Source: 1) Conversation with traffic engineers at Caltrans District 4
2) Banks and Kelly, 1997
3) JHK, 1992

Benefit - Cost Analysis

Total Benefit Streams

The streams of benefit values (in FY95 dollars) are shown in Table 14. Present value of benefit (PVB) is computed by applying discount rate to total benefit as shown:

$$PVB_k = \frac{TB_k}{(1+i)^k}$$

where PVB_k is present value of benefit in year k, TB_k is total benefit in year k, and i is discount ratio. This study uses 5% discount ratio as in Gillen et al., (1999).

Table 14 shows that passenger time saving consists of about 90% of net benefit, and vehicle emission is increased by ramp metering.

Table 14 Total Benefit Streams (FY95$)

Year	Fuel Saving	Time Saving	Emission	Total Benefit	PVB
1	86,338	783,485	-284	869,540	828,134
2	72,578	658,618	-558	730,638	662,710
3	75,605	686,083	-689	760,998	657,379
4	86,647	786,286	-917	872,016	717,410
5	100,791	914,632	-799	1,014,623	794,984
6	139,022	1,261,569	-879	1,399,712	1,044,487
7	165,344	1,500,423	-886	1,664,881	1,183,200
8	207,830	1,885,974	-888	2,092,916	1,416,568
9	283,592	2,573,482	-1,034	2,856,040	1,841,029
10	207,946	1,887,023	-1,028	2,093,941	1,285,498
Total	1,425,694	12,937,575	-7,964	14,355,305	10,431,397

Total Costs

The streams of cost values (in FY95$) are shown in Tables 15, 16, 17 for cases 1, 2, and 3 respectively. Present value of cost is also calculated by applying discount rate to total cost as PVB above.

Table 15 Total Cost Streams of Case 1

Year	Construction	Maintenance	Total Cost	PVC
0	750,000	-	750,000	750,000
1	-	75,000	75,000	71,429
2	-	75,000	75,000	68,027
3	-	75,000	75,000	64,788
4	-	75,000	75,000	61,703
5	-	75,000	75,000	58,764
6	-	75,000	75,000	55,966
7	-	75,000	75,000	53,301
8	-	75,000	75,000	50,763
9	-	75,000	75,000	48,346
10	-	75,000	75,000	46,043
Total	750,000	750,000	1,500,000	1,329,130

Table 16 Total Cost Streams of Case 2

Year	Construction	Maintenance	Total Cost	PVC
0	300,000	-	300,000	300,000
1	-	30,000	30,000	28,571
2	-	30,000	30,000	27,211
3	-	30,000	30,000	25,915
4	-	30,000	30,000	24,681
5	-	30,000	30,000	23,506
6	-	30,000	30,000	22,386
7	-	30,000	30,000	21,320
8	-	30,000	30,000	20,305
9	-	30,000	30,000	19,338
10	-	30,000	30,000	18,417
Total	300,000	300,000	600,000	531,652

Table 17 Total Cost Streams of Case 3

Year	Construction	Maintenance	Total Cost	PVC
0	113,024	-	113,024	113,024
1	-	2,192	2,192	2,088
2	-	2,192	2,192	1,988
3	-	2,192	2,192	1,894
4	-	2,192	2,192	1,803
5	-	2,192	2,192	1,717
6	-	2,192	2,192	1,636
7	-	2,192	2,192	1,558
8	-	2,192	2,192	1,484
9	-	2,192	2,192	1,413
10	-	2,192	2,192	1,346
Total	113,024	134,944	247,968	129,950

Total net benefit of ramp metering is summarized in Table 18. Total net benefit value in the lifetime of ramp meter would be about $9.1 million, $9.9 million and $10.3 million for cases 1, 2, and 3 respectively. The benefit-cost ratio are calculated as:

$$B/C\ Ratio = \frac{\sum_{k=1}^{K} PVB_k}{\sum_{k=1}^{K} PVC_k}$$

where PVB_k is present value of benefit in year k and PVC_k is total benefit in year k. The internal rate of return (IRR) is the discount rate required to make the present value of total benefits equal to the present value of total costs:

$$\sum_{k=0}^{K} \frac{TB_k}{(1+i)^k} = \sum_{k=0}^{K} \frac{TC_k}{(1+i)^k}$$

where TB_k is total benefit in year k, TC_k is total cost in year k, and i is the internal rate of return.

Table 18 Total Net Benefit (FY95$)

Year	PVB	Case 1		Case 2		Case 3	
		PVC	NPV	PVC	NPV	PVC	NPV
0	0	750,000	-750,000	300,000	-300,000	113,024	-113,000
1	828,134	71,429	756,705	28,571	799,562	2,088	826,038
2	662,710	68,027	594,683	27,211	635,499	1,988	660,715
3	657,379	64,788	592,591	25,915	631,464	1,894	655,479
4	717,410	61,703	655,707	24,681	692,729	1,803	715,600
5	794,984	58,764	736,219	23,506	771,478	1,717	793,260
6	1,044,487	55,966	988,521	22,386	1,022,100	1,636	1,042,845
7	1,183,200	53,301	1,129,899	21,320	1,161,879	1,558	1,181,636
8	1,416,568	50,763	1,365,805	20,305	1,396,263	1,484	1,415,079
9	1,841,029	48,346	1,792,683	19,338	1,821,690	1,413	1,839,611
10	1,285,498	46,043	1,239,455	18,417	1,267,081	1,346	1,284,147
Total	10,431,397	1,329,130	9,102,267	531,652	9,899,745	129,950	10,301,409

Benefit-Cost ratios and internal rate of returns (IRR) are illustrated in Table 19 for the three cases. The benefit-cost ratio of each case is 7.85, 19.62 and 80.25 respectively, and IRR is 103.04%, 269.29% and 753.72% respectively, indicating ramp metering is certainly worth implementing under the established assumptions including travel demand.

Table 19 Benefit-Cost Ratio and IRR

	Case 1	Case 2	Case 3
B/C ratio	7.85	19.62	80.25
NPV ($million)	9.10	9.90	10.30
IRR (%)	103.04	269.29	753.72

Sensitivity Analysis

The benefit-cost analysis is performed based on a few assumptions such as fuel consumption, value of passenger time, base year travel demand and capacity reduction at queue present. In this section, the effect of these assumptions is analyzed. Since previous analysis shows rather high values for B/C ratio, NPV and IRR, sensitivity analysis is made only for the cases in which benefits are reduced, costs are assumed to remain unchanged.

<u>Effect of fuel consumption</u>

We assume earlier that the average fuel economy is 25 miles per gallon. To estimate underestimating fuel consumption savings, lower average fuel consumption of 30 miles per gallon to 25 miles per gallon is assumed. This results in a 20% increase in fuel used. As a result the estimates of fuel consumption saving is reduced by about 16.7%, and total benefit decreases to about 98.3% of the previous level of benefits. Because fuel saving does not make a significant contribution to total benefit, the modification of reduced fuel economy results in a decrease in the previous measure of total benefits of only about 1.7%.

Table 20 Change of Annual Fuel Consumption Reduction

Year	Delay Saving (veh-hr)	Previous Value of Fuel Saving (FY95$)	New Value of Fuel Saving (FY95$)	Change of Value of Fuel Saving (FY95$)
1	32,704	86,338	71,949	-14,390
2	27,492	72,578	60,482	-12,096
3	28,638	75,605	63,004	-12,601
4	32,821	86,647	72,206	-14,441
5	38,178	100,791	83,992	-16,798
6	52,660	139,022	115,852	-23,170
7	62,630	165,344	137,786	-27,557
8	78,724	207,830	173,192	-34,638
9	107,421	283,592	236,327	-47,265
10	78,767	207,946	173,288	-34,658

Table 21 Change of Annual Total Benefit

Year	Delay Saving (hour)	Previous PVB (FY95$)	New PVB (FY95$)	Change of PVB (FY95$)
1	32,704	828,134	814,429	-13,705
2	27,492	662,710	651,738	-10,972
3	28,638	657,379	646,494	-10,885
4	32,821	717,410	705,529	-11,881
5	38,178	794,984	781,822	-13,162
6	52,660	1,044,487	1,027,197	-17,290
7	62,630	1,183,200	1,163,615	-19,584
8	78,724	1,416,568	1,393,123	-23,445
9	107,421	1,841,029	1,810,561	-30,468
10	78,767	1,285,498	1,264,221	-21,277

Effect of time value

Under the previous assumption, the hourly time value was assumed to be $12.75 per hour for auto and bus travelers, and $33.41 per hour for truck drivers. These values may be overestimated. To investigate the effect of lower values of time value , we substitute the previous assumption with a more conservative time values as used in Gillen et al. (1999),: $9.00 per hour for auto and bus travelers, and $23.40 per hour for truck drivers. As shown in Tables 18 and 19, the modification of hourly time value reduces value of time saving and totals benefit by 29.5% and 26.5% respectively. Though this modification of hourly time value appears to make significant reduction of benefit, the B/C ratio, NPV and IRR indicate that ramp metering is still worth implementing.

Table 22 Change of Annual Time Saving

Year	Delay Saving (veh-hr)	Previous Value of Time Saving (FY95$)	New Value of Time Saving (FY95$)	Change of Value of Time Saving (FY95$)
1	32,704	783,485	552,711	-230,774
2	27,492	658,618	464,623	-193,995
3	28,638	686,083	483,998	-202,085
4	32,821	786,286	554,687	-231,599
5	38,178	914,632	645,228	-269,403
6	52,660	1,261,569	889,976	-371,593
7	62,630	1,500,423	1,058,476	-441,947
8	78,724	1,885,974	1,330,463	-555,510
9	107,421	2,573,482	1,815,467	-758,015
10	78,767	1,887,023	1,331,204	-555,819

Table 23 Change of Annual Total Benefit

Year	Delay Saving (hour)	Previous PVB (FY95$)	New PVB (FY95$)	Change of PVB (FY95$)
1	32,704	828,134	608,349	-219,785
2	27,492	662,710	486,751	-175,959
3	28,638	657,379	482,811	-174,568
4	32,821	717,410	526,873	-190,537
5	38,178	794,984	583,899	-211,084
6	52,660	1,044,487	767,198	-277,288
7	62,630	1,183,200	869,116	-314,084
8	78,724	1,416,568	1,040,577	-375,991
9	107,421	1,841,029	1,352,406	-488,623
10	78,767	1,285,498	944,273	-341,225

Table 24 B/C ratio and NPV

	Case 1	Case 2	Case 3
B/C ratio	5.76	14.41	58.95
NPV ($million)	6.33	7.13	7.53
IRR (%)	75.49	194.34	550.24

<u>Effect of Demand Change</u>

Travel delay is caused when travel demand exceeds roadway capacity. Ramp metering is to regulate entering traffic through the on-ramp so that free flow traffic can be achieved by maintaining traffic flow below or close to capacity. Therefore, the effect of ramp metering is a function of travel demand. In other words, the benefit of ramp metering can vary by a change in demand. To see the effect of a demand change on the magnitude of benefits, we change ramp travel demand and freeway demand. First, ramp demand is decreased by 50% of that previously used. Due to the decrease of ramp demand, the period of demand excess becomes shorter and its magnitude is smaller (see Table 25). As expected, benefits (fuel consumption and time saving) are reduced. Table 26 displays streams of annual benefit. For the first four years, travel demand remains lower than capacity and travel delay does not occur. Ramp does not need to be metered. Starting from the fifth year, demand excess occurs and ramp metering generates benefits by reducing travel delay. Total benefits are reduced to $4.56 million from $10.43 million (see Table 27). Though B/C Ratio, NPV and IRR indicate that ramp metering is still worth implementing, we can delay the implementation of ramp metering until the fifth year to maximize net benefit.

Table 25 Period and Magnitude of Demand Excess

(50 % reduction of ramp demand)

Year[1)]	Begin[2)] (sec)	End[3)] (sec)	Duration (sec)	Excess[4)] (veh)	Excess[5)] (vph)
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	26,800	28,068	1,268	19	54
6	26,592	28,408	1,816	56	111
7	26,388	28,740	2,352	108	165
8	26,188	29,256	3,068	175	205
9	25,880	29,824	3,944	261	238
10	25,500	30,456	4,956	373	271

Note: 1) Year after base year.
2) Time travel demand at merge cell starts higher than capacity in second since midnight.
3) Time travel demand at merge cell returns to below capacity in second since midnight.
4) Total number of vehicles exceeding capacity
5) Hourly rate of vehicles exceeding capacity

Table 26 Total Vehicle-hours and Travel Delay at Morning Peak

(50 % reduction of ramp demand)

Year	Without Metering		With Metering		Change			
	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Net Change (veh-hr)	Average[1)] (sec/veh)[1)]
1	319.0	-	319.0	-	-	-	-	-
2	323.8	-	323.8	-	-	-	-	-
3	328.7	-	328.7	-	-	-	-	-
4	333.6	-	333.6	-	-	-	-	-
5	401.0	1.2	338.6	6.3	62.4	-5.1	57.3	10.9
6	488.6	1.6	384.2	43.6	104.3	-42.0	62.3	11.6
7	619.8	1.9	498.1	59.9	121.8	-58.0	63.7	11.7
8	806.9	2.2	661.0	74.7	145.8	-72.5	73.3	13.3
9	1,077.8	2.5	892.2	90.4	185.6	-87.9	97.7	17.4
10	1,462.2	2.9	1227.6	107.8	234.6	-104.9	129.6	22.8

Note: 1) Net travel delay change divided by total travel demand for the entire simulation period.

Table 27 Total Benefit Streams

(50 % reduction of ramp demand, FY95$)

Year	Fuel Saving	Time Saving	Emission	Total Benefit	PVB
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	78,970	716,616	-330	795,255	623,103
6	85,859	779,135	-765	864,229	644,901
7	87,826	796,983	-955	883,855	628,139
8	100,979	916,342	-1,132	1,016,189	687,797
9	134,656	1,221,951	-1,015	1,355,592	873,827
10	178,665	1,621,306	-1,068	1,798,903	1,104,370
Total	666,954	6,052,333	-5,265	6,714,023	4,562,137

Table 28 B/C ratio, NPV and IRR

(50 % reduction of ramp demand)

	Case 1	Case 2	Case 3
B/C ratio	3.43	8.58	35.10
NPV ($million)	3.23	4.03	4.43
IRR (%)	28.61	48.61	76.70

To see the effect of a reduction in freeway demand, we reduce the previously used freeway demand by 10%. This reduction delays the occurrence of demand excess (Table 29). For the first five years, travel demand is lower than capacity and the ramp is not metered during the first five years. This decrease in freeway demand reduces ramp-metering benefits to $2.51 million from $10.43 million. As with the case of reducing ramp demand, the calculated values of the B/C Ratio, NPV and IRR indicate that ramp metering is still worth implementing. However, we can delay the implementation of ramp metering until the sixth year to maximize benefit.

Table 29 Period and Magnitude of Demand Excess

(10 % reduction of freeway demand)

Year	Begin[1)] (sec)	End[2)] (sec)	Duration [3)] (sec)	Excess[4)] (veh)	Excess[5)] (vph)
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	-	-	-	-	-
6	26,884	28,132	1,248	22	63
7	26,720	28,396	1,676	61	131
8	26,556	28,648	2,092	111	191
9	26,400	28,984	2,584	173	241
10	26,244	29,540	3,296	252	275

Note: 1) Time travel demand at merge cell starts higher than capacity in second since midnight.
2) Time travel demand at merge cell returns to below capacity in second since midnight.
3) Duration demand exceeds capacity.
4) Total number of vehicles exceeding capacity
5) Hourly rate of vehicles exceeding capacity

Table 30 Total Vehicle-hours and Travel Delay at Morning Peak
(10 % reduction of freeway demand)

Year	Without Metering		With Metering		Change			
	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Net Change (veh-hr)	Average [1] (sec/veh)
1	288.2	-	288.2	-	-	-	-	-
2	292.6	-	292.6	-	-	-	-	-
3	297.0	-	297.0	-	-	-	-	-
4	301.5	-	301.5	-	-	-	-	-
5	306.1	-	306.1	-	-	-	-	-
6	361.4	2.8	310.7	7.0	50.7	-4.2	46.5	9.0
7	435.1	3.7	349.0	39.0	86.1	-35.3	50.8	9.7
8	546.4	4.4	446.3	53.9	100.1	-49.5	50.6	9.5
9	701.7	5.1	584.4	66.4	117.3	-61.3	56.1	10.4
10	911.3	5.8	773.6	78.8	137.7	-73.0	64.7	11.8

Note: 1) Net travel delay change divided by total travel demand for the entire simulation period.

Table 31 Total Benefit Streams
(10 % reduction of freeway demand, FY95$)

Year	Fuel Saving	Time Saving	Emission	Total Benefit	PVB
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	-	-	-	-	-
6	64,105	581,723	-163	645,665	481,805
7	69,993	635,156	-423	704,727	500,836
8	69,771	633,147	-563	702,356	475,382
9	77,242	700,935	-808	777,368	501,098
10	89,172	809,198	-739	897,630	551,067
Total	370,282	3,360,159	-2,695	3,727,746	2,510,189

Table 32 B/C ratio and NPV
(10 % reduction of freeway demand, FY95$)

	Case 1	Case 2	Case 3
B/C ratio	1.89	4.72	19.31
NPV ($million)	1.18	1.98	2.38
IRR (%)	16.39	33.50	56.74

In the traffic simulation, we assume that the capacity of the downstream merge cell is decreased to be 97% of normal capacity. The literature indicates that this capacity reduction may vary due to a number of factors including traffic levels and roadway geometry. To see the effect of a change in the capacity, we adjust it to 98% and 99% of normal capacity. As expected, the travel delay reduction due to ramp metering is decreased, see (Tables 33 and 36). The total present value of benefits is reduced to $6.6 million and $3.2 million from

$10.4 million respectively (Tables 34 and 37). The values of the B/C Ratio, NPV and IRR (Tables 34 and 37), however, indicate that even under these new assumptions, ramp metering is still worth implementing.

Table 33 Total Vehicle-hours and Travel Delay at Morning Peak

(2 % capacity reduction at queue present)

Year	Without Metering		With Metering		Change			
	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Net Change (veh-hr)	Average [1)] (sec/veh)
1	363.0	2.1	320.0	11.6	42.9	-9.5	33.5	6.4
2	430.8	2.9	361.8	40.1	69.0	-37.2	31.8	6.0
3	536.1	3.5	452.0	54.2	84.1	-50.7	33.4	6.2
4	685.7	4.1	584.3	66.7	101.3	-62.6	38.7	7.1
5	889.6	4.6	769.8	79.4	119.8	-74.8	45.1	8.1
6	1,177.2	5.3	1,026.2	93.9	151.0	-88.5	62.5	11.1
7	1,568.4	6.1	1,385.3	109.1	183.0	-103.1	80.0	13.9
8	2,024.9	6.5	1,818.3	112.6	206.6	-106.1	100.5	17.2
9	2,608.3	7.3	2,357.0	121.5	251.4	-114.2	137.2	23.1
10	3,160.8	7.7	2,940.8	127.1	220.0	-119.4	100.6	16.7

Note: 1) Net travel delay change divided by total travel demand for the entire simulation period.

Table 34 Total Benefit Streams (FY95$)

(2 % capacity reduction at queue present)

Year	Fuel Saving	Time Saving	Emission	Total Benefit	PVB
1	46,146	418,751	-204	464,693	442,565
2	43,844	397,863	-459	441,248	400,225
3	46,046	417,848	-588	463,306	400,221
4	53,338	484,019	-818	536,538	441,412
5	62,103	563,560	-761	624,902	489,627
6	86,067	781,018	-812	866,273	646,426
7	110,209	1,000,103	-886	1,109,426	788,448
8	138,534	1,257,137	-863	1,394,808	944,061
9	189,042	1,715,475	-984	1,903,533	1,227,035
10	138,611	1,257,837	-996	1,395,452	856,686
Total	913,939	8,293,610	-7,370	9,200,179	6,636,706

Table 35 B/C ratio, NPV and IRR

(2 % capacity reduction at queue present)

	Case 1	Case 2	Case 3
B/C ratio	4.99	12.48	51.06
NPV ($million)	5.31	6.11	6.51
IRR (%)	60.61	146.79	406.65

Table 36 Total Vehicle-hours and Travel Delay at Morning Peak
(1 % capacity reduction at queue present)

Year	Without Metering		With Metering		Change			
	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Freeway (veh-hr)	Ramp (veh-hr)	Net Change (veh-hr)	Average [1)] (sec/veh)
1	343.2	1.8	320.0	11.6	23.2	-9.8	13.4	2.6
2	391.6	2.5	346.1	33.9	45.4	-31.4	14.0	2.7
3	475.5	3.2	414.1	49.3	61.3	-46.1	15.2	2.8
4	598.8	3.7	523.5	61.3	75.3	-57.5	17.8	3.3
5	770.7	4.3	680.5	73.6	90.2	-69.3	20.9	3.8
6	1,010.8	4.9	899.8	87.0	110.9	-82.0	28.9	5.1
7	1,343.9	5.7	1,207.9	103.2	136.0	-97.5	38.5	6.7
8	1,775.3	6.3	1,618.7	112.6	156.6	-106.3	50.2	8.6
9	2,316.6	7.0	2,133.6	121.5	183.0	-114.4	68.6	11.5
10	2,858.7	7.4	2,688.8	127.1	169.9	-119.6	50.3	8.3

Note: 1) Net travel delay change divided by total travel demand for the entire simulation period.

Table 37 Total Benefit Streams (FY95$)
(1 % capacity reduction at queue present)

Year	Fuel Saving	Time Saving	Emission	Total Benefit	PVB
1	18,426	167,210	-153	185,484	176,651
2	19,337	175,472	-355	194,453	176,375
3	20,990	190,477	-503	210,964	182,239
4	24,514	222,455	-628	246,341	202,666
5	28,747	260,867	-773	288,841	226,314
6	39,774	360,931	-742	399,963	298,459
7	53,075	481,631	-829	533,878	379,417
8	69,237	628,299	-863	696,674	471,536
9	94,491	857,469	-924	951,036	613,046
10	69,276	628,650	-954	696,972	427,881
Total	437,867	3,973,463	-6,724	4,404,606	3,154,583

Table 38 B/C ratio, NPV and IRR
(1 % capacity reduction at queue present)

	Case 1	Case 2	Case 3
B/C ratio	2.37	5.92	24.27
NPV ($million)	1.83	2.62	3.02
IRR (%)	27.68	65.92	170.55

Conclusion

In this report, we have followed the steps described in *Evaluation Methodologies for ITS Applications* (Gillen et al., 1998) and undertaken a benefit-cost analysis for ramp metering. The impact of ramp metering on traffic behavior is simulated based on the cell transmission model and assumed levels of travel demand on both the freeway and the ramp. Temporal travel demand change is determined based on the average travel pattern obtained from the I-880 freeway database. Isolated, single traffic responsive ramp metering is assumed. We identified and quantified the benefits and costs of ramp metering project based on established assumptions, and finally analyzed economic value of ramp metering. Benefits of ramp metering are derived based on travel time value and fuel consumption by saving in travel delay. In this study, it turns out that more vehicle emissions result with the introduction of ramp metering.

The costs of ramp metering are site dependent and a function of planned metering technology. Since this study is not for any specific site, costs are estimated for three cases with data obtained either from conversation with traffic engineers at Caltrans District 4 or from the literature.

Under the original assumptions for fuel economy, time value and travel demand on the freeway and the ramp, ramp metering generates a NPV of $10.44 million. For all three cost scenarios, ramp metering turns out to be worthwhile implementing (Tables 18 and 19).

To see the effect of changes in the assumptions, we conducted sensitivity analysis. Since the original assumptions yield results that are favorable to ramp metering, we focused on changing the assumptions to reduce benefits. A change in the assumed level of fuel economy does not make a significant change in the measure of benefit (1.6 % of previous total benefits). Since time saving is the major source of benefits, a change of time value reduces benefits by 26.5 % (Table 23). Nonetheless, ramp metering is still worthwhile implementing based on all three measures of B/C ratio, NPV and IRR (Table 24). Ramp demand is reduced to 50% of the previous level. This reduction of ramp demand results in the level of travel demand being less than capacity for the first four years. As a result the ramp is not metered and does not generate any benefits until after the forth year. Benefit-cost analysis under this scenario shows ramp metering is worth implementing (Table 28), but the ramp metering implementation can be postponed until the forth year to maximize net benefits. This is because construction and maintenance incur costs but travel demand is less than capacity and the metered ramp is not implemented for the first four year. Freeway demand is reduced to 10% of previous demand. This reduction of freeway demand results in travel demand being less than capacity until the first five years. As in the case of ramp demand reduction, though benefit-cost analysis indicates ramp metering is worth implementing (Table 32), the implementation can wait till the fifth year to maximize net benefits.

In the traffic simulation, any capacity reduction at queue present plays a major role in generating traffic delay. Sensitivity analysis for different values of capacity reduction is also conducted. Two different cases of capacity reduction are analyzed: 98% and 99% of normal capacity. The amount of travel delay reduction by ramp metering is decreased by about 64%

and 31% respectively. However, ramp metering still is worthwhile implementing (Tables 34 and 37).

This study provides a spreadsheet model for benefit-cost analysis of ramp metering. Using the model, users can analyze a ramp-metering system that they plan to implement. The restriction is that the ramp meter must be a single isolated one.

This study has its limitations and can be extended in a number of different ways. First, even with a single ramp meter we did not take account of costs associated with any spillover traffic onto arterial roads behind the ramp. In other words the model assumes the ramp queue is fully contained on the ramp. A more sophisticated network model is needed to take account of these spillover effects. A second extension is to consider ramp meters used in parallel so they are complementary

References

Banks, J. (1990), Flow processes at a freeway bottleneck, *Transportation Research Record* 1287.

Banks, J. (1991), Two-capacity phenomenon at freeway bottlenecks: a basis for ramp metering ?, *Transportation Research Record* 1320.

California Air Service Board (19?), Methodology for estimating emissions from on-road motor vehicles, downloaded from "http://www.arb.ca.gov/msei/mvei/mvdocs.html".

CalTrans. (1991), Ramp Metering Design Guidelines. January

Chen, C., J.B. Cruz, and J.G. Paquet (1974), Entrance ramp control for travel-rate maximization in expressways, *Transportation Research*, Vol. 8.

Chin, C (1996), An integrated dynamic control model with signals, ramp meterings, and route guidance, *Transportation Planning Journal*, Vol. 25, no. 3.

Daganzo, C. (1993), The cell transmission model Part I: a simple dynamic representation of higheay traffic, California PATH Research report, UCB-ITS-PRR-97-7, Institute of Transportation Studies, University of California, Berkeley.

Drew, D.R., W.R. McCasland, C. Pinnell, J.A. Wattleworth, and J.H. Buhr (1967), Gap acceptance in the freeway merging process, *Highway Research Record* 244.

Drew, Donald; William McCasland; Charles Pinnell; Joseph Wattleworth. (1966) The Development of an Automatic Freeway Merging Control System. Research Report 24-19.

Gillen, D., J. Li, J. Dahlgren, and E. Chang (1999), Assessing the benefits and costs of ITS projects: volume 2 an application to electronic toll collection, California PATH Research Report, UCB-ITS-PRR-99-10, Institute of Transportation Studies, University of California, Berkeley.

Hurdle, V., and P. Datta (1989), Speeds and flows on an urban freeway: some measurements and a hypothesis, *Transportation Research Record* 905.

ITSA Fact Sheets (1995), Development of advanced traffic management systems in the US by State agencies, March 1, 1995.

JHK & Associates (1992), Operational procedures and strategies: conceptual design report, Contract # 04-D922-PC.

Keen, K.G., M.J. Schofield, and R. Bannon (1988), Access control by ramp metering on M6, Proceedings of Seminar at the PTRC Transport and Planning Summer Annual Meeting, Unversity of Bath, England.

Lighthill, M.J., and G.B. Whitham (1955), On kinematic waves: II. A theory of traffic flow on long crowded roads, Proceedings of Royal Society, London, Series A 229.

Meldrum, D. and C. Taylor (1995), Freeway traffic data prediction using artificial neural networks and development of a fuzzy logic ramp metering algorithm, WA-RD 365.1, Washington State Dept. of Transportation, Olympia WA.

Munjal, P.K., Y.S. Hsu, and R.L. Lawrence (1973), Prediction and Stability of Freeway Gaps and On-ramp Merging, *Highway Research Record* 469.

Newman, Leonard, Alex Dunnet, and Gary Meis. (1969) Freeway Ramp Control- What It Can and Cannot Do. Freeway Operation Department, District 7, California Division of Highways. February.

Papageorgiou, M., H. Hadj-Salem, and J. Blosseville (1991), ALINEA: A local feedback control law for on-ramp metering, *Transportation Research Record* 1320.

Papageorgiou, M., J Blowweville, and H. Hadj-Salem (1990), Modeling and real-time control of traffic flow on the southern part of Boulevard Peripherique in Paris: Part II: Coordinated on-ramp metering, *Transportation Research A*, Vol. 24A.

Parsons Transportation Group and Texas Transportation Institute. (1997) Estimation of Benefits of Houston TranStar. February.

Piotrowicz, G. and J. Robinsons (1995), Ramp metering status in north America, DOT-T-95-17, Federal Highway Administration.

Richards, P.L. (1956), Shock waves on the highway, *Operations Research*, Vol. 4.

Skabardonis, A., H. Noeimi, K. Petty, D. Rydzewsik, P. Varaiya, and H. Al-Deek (1995), Freeway service patrol evaluation, California PATH Research Report, UCB-ITS-PRR-95-5, Institute of Transportation Studies, University of California, Berkely.

Small, K. and C. Kazimi (1995), On the cost of air pollution from motor vehicles, *Journal of Transport Economics and Policy*.

Wattleworth, J.A. (1967), Peak-period analysis and control of a freeway system, *Highway Research Record* 157.

Wattleworth, J.A., C.E. Wallace, and M.Levin (1967), Development and preliminary evaluation of a ramp metering system on the Lodge Freeway, Report of National Coorperative Highway Research Project 20-3.

Yagoda, H.N., and L.J. Pignataro (1970). The analysis and design of freeway entrance ramp control systems. *Highway Research Record* 303.

Zhang, H. (1995), A new framework for optimal freeway ramp control, Ph.D. Dissertation, University of California, Irvine.

Appendix

MVE17G Emission Factors (Unit: grams per mile)

Speed (mph)	ROG			CO			Nox		
	Auto	Truck	Bus	Auto	Truck	Bus	Auto	Truck	Bus
5	0.91	1.46	5.62	17.09	20.98	7.89	1.07	2.05	32.75
10	0.43	0.96	4.08	9.71	13.96	4.96	0.80	2.15	25.05
15	0.30	0.65	3.06	6.67	9.81	3.32	0.64	2.26	20.14
16	0.29	0.61	2.91	6.29	9.20	3.08	0.61	2.28	19.40
20	0.26	0.47	2.38	5.17	7.29	2.35	0.53	2.36	17.03
25	0.24	0.35	1.92	4.30	5.72	1.77	0.46	2.46	15.13
30	0.22	0.27	1.60	3.72	4.74	1.42	0.44	2.57	14.14
35	0.20	0.22	1.39	3.30	4.15	1.21	0.45	2.67	13.88
40	0.17	0.18	1.24	3.01	3.84	1.09	0.49	2.78	14.34
45	0.14	0.16	1.15	2.88	3.76	1.04	0.57	2.88	15.56
50	0.13	0.14	1.10	3.01	3.88	1.06	0.69	2.98	17.76
55	0.14	0.14	1.10	3.63	4.24	1.14	0.84	3.09	21.30
60	0.21	0.14	1.13	5.46	4.88	1.31	1.03	3.19	26.86

Source: California Air Service Board

USER'S MANUAL FOR

COMPUTERIZED BENEFIT-COST ANALYSIS OF RAMP METERING

By Seungmin Kang and David Gillen

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This document describes the steps to use the Ramp Metering Benefit-Cost Analysis Model. It assumes the user has limited familiarity with Excel or a similar spreadsheet as well as with benefit cost analysis.

A. **Introduction**

This model consists of two categories of worksheets and two macros. Two worksheets that are contained in this file are:

1. *Inputs*: Data needed to input to perform the analysis.
   - Input data for traffic simulation
   - Assumed economy of fuel consumption and value of time saving
   - Factors of vehicle emission by speed range
   - Cost associated with ramp metering implementation

2. *Outputs*: Intermediate calculations of saving of travel delay, vehicle emission reduction, and results from the analysis, including the net present value of benefits and costs, benefit/cost ratio, and internal rate of return.
   - Vehicle delay
   - Vehicle emission
   - Results from Benefit/Cost Analysis

Two macro files are written to perform traffic simulation ("*traffic_simulation*") and to compute benefit/cost analysis ("*B_C_analysis*") for given input.

The quickest way to apply the model is to learn by doing. Simply follow the instructions.

An overview of the model procedure is presented in the next section.

B. **Model Overview**

The system is very simple to use at its most basic level. Begin by:

1. Copy the file "ramp_metering.xls" to a new file name (for instance MYFILE.XLS).
2. Open the new file in Microsoft Excel 97.
3. Go to the four input pages "*input*(*traffic*)", "*input*(*fuel&travel time saving*)", "*input*(*emission*)" and "*input*(*cost*)", and fill out all cells requested which are marked by a yellow color.
4. Run the macro file, "*traffic_simulation*" to simulate traffic for given traffic conditions, which are provided in the file "*input*(*traffic*)". To perform benefit/cost analysis, run the macro file "*B_C_analysis*.
5. Go to the page "*output*(*vehicle-hour*)" to get travel delay saving by ramp metering. Go to the page "*output*(*emission*)" to get vehicle emissions estimated without ramp metering and with ramp metering. Go to the page "*output*(*B-C*)" to

get Net Present Value of the project, Benefit-Cost Ratio, and the estimated Internal Rate of Return. All results are marked by yellow color.

C. **Input Sheets**

Four kinds of input sheets are used in this model.

The file "*input*(*traffic*)" includes information required for traffic simulation:

- *No of Freeway Lane*: Total number of lanes on the study freeway
- *No of Ramp Lane*: Total number of lanes on ramp
- *Freeway Length* (*ft*): Length of freeway upstream to the merge point
- *Analysis Period* (*AM*): Start and end time of morning peak period
- *Analysis Period* (*PM*): Start and end time of afternoon peak period
- *Meter Update* (*second*): Period of time that meter rate is updated. This will determine the length of the cell in the traffic simulation along with free-flow speed.
- *Travel Demand Update* (*minute*): Period of time that travel demand on freeway and ramp is updated.
- *Freeway Demand at AM*: The number of cells that are required to be filled in is determined by "*Analysis Period* (*AM*)" and "*Travel Demand Update*". For example, if "Analysis Period (AM)" is 6 to 10 AM and "Travel Demand Update" is 15 minute, the user is supposed to provide travel demand on freeway from 6 to 10 AM at every 15 minute interval(6:00, 6:15, 6:30, etc.), which would mean there are 17 cells in total (for this example). Travel demand between two consecutive periods is obtained by interpolating travel demand at the periods.
- *Ramp Demand at AM*: User is supposed to provide ramp travel demand at the same interval as "*Freeway Demand at AM*".
- *Freeway Demand at PM*: As in Freeway Demand at AM, depending on *"Analysis Period* (*PM*)" and "*Travel Demand Update*", the number of cells required to fill in is determined.
- *Ramp Demand at PM*: User is supposed to provide ramp travel demand at the same interval as "*Freeway Demand at PM*".
- *Free Speed* (*mph*): Free-flow speed on freeway.
- *Wave Speed* (*mph*): Speed that queue is propagating backward.
- *Critical Density* (*vehicle/mile/lane*): Number of vehicles on freeway at capacity.
- *Jam Density* (*vehicle/mile/lane*): Maximum number of vehicles that can be present on the freeway
- *Capacity* (*vehicle/hour/lane*): Maximum flow rate on freeway.
- *Reduced Capacity* (*%*): Capacity reduction downstream to the merge cell at queue present.
- *Max. Ramp Queue* (*vehicle/lane*): Maximum number of vehicles that ramp can hold on a lane. Total maximum queue is calculated as the product of "*No of Ramp Lane*" and "*Max. Ramp Queue*".
- *Life Time of Ramp* (*year*): Assumed or estimated length of life time of ramp. This model assumes 10-year life time.

- *Annual Increase Rate of Freeway Demand* (*%*): Assumed or estimated rate of freeway demand increases at each year. This rate is applied to obtain future travel demand on freeway.
- *Annual Increase Rate of Ramp Demand* (*%*): Assumed or estimated rate of freeway demand increases at each year. This rate is applied to obtain future travel demand on ramp.
- *Change of Freeway Demand* (*%*): This is for sensitivity analysis. For instance, if user wants to simulate traffic condition with lower travel demand than that provided in "*Freeway Demand at AM*" and "Freeway Demand at PM", put number lower than 100.
- *Change of Ramp Demand* (*%*): This is for sensitivity analysis. As in *"Change of Freeway Demand* (*%*)", user puts number lower or higher than 100 depending on the level of ramp demand that user wants.

The file "*input*(*fuel & travel time saving*)" includes information about fuel economy, ratio of vehicle and value of time saving.

- *Average Travel Speed* (*mph*): Average speed that vehicle travels under normal traffic condition.
- *Average Fuel Consumption* (*mile/gallon*): How far you can go in average by using one unit of fuel.
- *Fuel Cost* (*$/gallon*): How much you have to pay in average to get one unit of fuel.
- *Ratio of Vehicles*: Split of vehicles traveling on freeway. Vehicles are categorized by auto, truck and bus.
- *Occupancy* (*persons/veh*): Average vehicle occupancy for each mode. This information along with the mode split tells the amount of time saved.
- *Value of time* (*$/hour*): Unit value of passenger time by mode.

The file "*input*(*emission*)" includes information about emission factors for reactive organic gases (ROG), carbon monoxide (CO) and oxides of nitrogen (NOx) recommended by California Air Service Board, emission rate at idle and economy of emission.

- *MVEI7G Emission Factors* (*grams/mile*)
- *Conversion* (*ROG to HC*): Since hydrocarbons (HC) are interested in this study, emission factor for ROG need to be converted for HC. This is the value used to convert emission factor for ROG to that for HC.
- *Idle Emission Rates* (*grams/minute*): Emission rate when vehicle idles.
- *Unit Costs by Pollutant* (*$/kg*): Estimated average cost of pollutant.

The file "*input* (*cost*)" includes cost required for construction and maintenance of ramp and discount ratio used for converting benefit or cost at current year to that at present year (e.g. 1999).

- *Construction*: Expenditures that occur at a specific point of time including cost associated with construction and improving on-ramp to support ramp metering.
- *Maintenance*: Cost associated with operation and maintenance of ramp metering.

- *Discount Ratio*: Value used to convert benefit or cost at current year to that at present year (e.g., 1999).

Note that all of values for input should be put in corresponding cells in yellow color.

D. **Output Sheets**

Three kinds of output sheets are offered in this model: "*output*(*vehicle-hour*)", "*output*(*emission*)", and "*output*(*B_C*)". The files "*output*(*vehicle-hour*)" and "*output*(*emission*)" is generated by running the macro "*traffic_simulation*". The file "*output*(*vehicle-hour*)" summarizes result of traffic simulation without ramp metering and with ramp metering.

- *Vehicle-hours and Travel Delay at Morning Peak*: Travel time on freeway and travel delay on ramp without ramp metering and with ramp metering at morning peak.
- *Vehicle-hours and Travel Delay at Afternoon Peak*: Travel time on freeway and travel delay on ramp without ramp metering and with ramp metering at afternoon peak.
- *Daily Vehicle-hours and Travel Delay*: Summation of "Vehicle-hours and Travel Delay at Morning Peak" and "Vehicle-hours and Travel Delay at Afternoon Peak".
- *Annual Travel Delay Reduction* (*veh-hr*): Difference of travel time on freeway and travel delay on ramp without ramp metering and those with ramp metering multiplied by weekdays (365 days/year – 2 x 52 weekends/year).

The file "*output*(*emission*)" summarizes estimates of vehicle emissions without ramp metering and with ramp metering at morning and afternoon peaks. Vehicle emissions are estimated for freeway and ramp separately. Vehicle emissions for freeway are estimated in two steps. First, compute speed of each cell in traffic simulation and apply emission factors recommend by California Air Service Board to get vehicle emission by pollutant. Vehicle emissions for ramp are estimated for vehicle waiting on ramp to enter freeway and are calculated by multiplying waiting time on ramp by emission rate at idling.

- *Estimates of Emissions at Morning Peak* (*kg*): Vehicle emissions estimated at morning peak.
- *Estimates of Emissions at Morning Peak* (*kg*): Vehicle emissions estimated at morning peak.
- *Daily Estimates of Emissions* (*kg*): Summation of "Estimates of Emissions at Morning Peak" and "Estimates of Emissions at Afternoon Peak".
- *Annual Estimates of Emission Change* (*kg*): Emissions calculated by multiplying weekdays (365 days/year – 2 x 52 weekends/year) to "Daily Estimates of Emissions".

The file "*output*(*B_C*)" is generated by running the macro "*B_C_anlaysis*" and summarizes fuel consumption reduction, passenger travel time saving, vehicle emission change, streams of benefit and cost, net present value, benefit-cost ratio and internal rate of return.

- *Annual Fuel Consumption Reduction*: Reduction of fuel consumption by ramp metering is computed by multiplying travel delay reduction by ramp metering by the average hourly fuel consumption:
  $VF_t = DS_t * S * C / F$

  where, VF_t is value of fuel saving in year *t* (FY95$), DS_t is delay saving in year *t*, *S* is average travel speed (mph), *C* is unit cost of fuel ($/gallon), and *F* is the average fuel consumption (mile/gallon).
- *Annual Passenger Timesaving*: Timesaving is calculated by multiplying the total delay saving by vehicle occupancy weighting factor:
-

  $$TS_t = \sum_{m=1}^{M} DS_t * W_m$$

  where $W_m = VOC_m * Ratio_m * VOT_m$

  TS_t is timesaving in year *t* (FY95$), *m* is a mode (auto, truck or bus), DS_t is delay saving in year *t*, W_m is weighting factor by mode *m*, VOC_m is occupancy of vehicle by mode *m*, $Ratio_m$ is a split of vehicle by mode *m*, VOT_m is value of time of passenger by mode *m*.
- *Estimates of Annual Vehicle Emissions Change* (*FY95$*): Value of vehicle emission is calculated by multiplying value of pollutant by its annual estimates of emission change computed in "*output*(*emission*)":

  $VE_m = VP_m * E_m$

  where VE_m is value of vehicle emission in year *t*, VP_m is value of pollutant *m*, and E_m is annual estimates of emission change.
- *Annual Benefit Stream* (*FY95$*): Fuel saving, time saving and emission change are all added to get annual benefit. Present value of benefit (PVB) is calculated by applying discount ratio (obtained in "*input*(*emission*)") to the annual benefit:

  $$PVB_t = \frac{TB_t}{(1+i)^t}$$

  where PVB_t is present value of benefit, TB_t is total benefit in *t*th year after base year, and *i* is discount ratio.
- *Annual Cost Stream* (*FY95$*): As in "Annual Benefit Stream", present value of cost (PVC) is calculated by applying discount ratio to the annual cost:

  $$PVC_t = \frac{TC_t}{(1+i)^t}$$

where PVC_t is present value of benefit, TC_t is total benefit in *t*th year after base year, and i is discount ratio.

- *Annual Net Benefit* (*FY95$*): Difference between annual benefit and annual cost.
- *Benefit Cost Ratio*: Ratio of total present value of benefit to total present value of cost.

$$B/C\ Ratio = \frac{\sum_{t=0}^{T} PVB_t}{\sum_{t=0}^{T} PVC_t}$$

- *Internal Rate of Return* (*IRR*): IRR is the discount ratio to make the present value of total benefit equal to the present value of total cost:

$$\sum_{t=0}^{T} \frac{TB_t}{(1+i)^t} = \sum_{t=0}^{T} \frac{TC_t}{(1+i)^t}$$

where TB_t is total benefit in year t, TC_t is total cost in year t, and i is the internal rate of return.

Additional Files

http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/99/PRR-99-19-01.xls