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EVALUATION OF THE POTENTIAL FOR USING RAMP METERING IN THE ATMS OF THE I-80 SHOWCASE CORRIDOR

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Submitted by

Steven I-Jy Chien
Principal Investigator, Associate Professor
New Jersey Institute of Technology
Dept. of Civil Environmental Engineering

Jiangtao Luo
Research Assistant
New Jersey Institute of Technology
Interdisciplinary Program in Transportation

NJDOT Research Project Manager
Robert Sasor

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Newark, New Jersey 07102-1982

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16. Abstract

Ramp metering was proven to be a viable form of freeway traffic control strategy, which could eliminate, or at least reduce, freeway congestion. In this study, general and technical requirements, ramp metering control strategies and models, and constraints (e.g., meter locations, ramp storage capacities, lower and upper bounds of ramp metering rates) were discussed in detail. Based on the collected geometric and traffic data, the CORSIM model was developed and used to simulate traffic operation of the study site. The pre-timed and demand/capacity metering control strategies were evaluated, while the potential metered ramps were determined. A dynamic multi-ramp metering control model with SPSA algorithm, which maximized the total throughput subject to a number of constraints, was developed and applied on single and multiple ramps of the study site. The potential benefit of the dynamic multi-ramp control model under time varying traffic demand was tested, simulated, and evaluated. The increased total throughput and reduced total delay were observed, while the traffic conditions suitable for implementing ramp metering control were suggested.

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Ramp Metering, Freeway, Dynamic Control, Simultaneous Perturbation Stochastic Approximation, Delay, Capacity, Simulation.

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LIST OF ABBREVIATION AND SYMBOLS

a	: the vehicle acceleration rate
a	: non-negative coefficients in SPSA
$\mathbf{a}_h$	: the parameter during the h^{th} iteration
c	: non-negative coefficients in SPSA
$\mathbf{c}_h$	: the parameter during the h^{th} iteration
d	: the travel distance
$\mathbf{g(\lambda)}$	: the gradient of $\mathbf{L(\lambda)}$
$\hat{g}(\hat{\lambda}_h)$	: the approximation of $g(\hat{\lambda}_h)$
h	: the counter index
L_i	: the physical length of link i
L_q	: the queue length (number of vehicles)
$\mathbf{L(\lambda)}$	: the objective function for minimization with the vector $\boldsymbol{\lambda}$
l_i	: the number of through lanes of link i
MAPE	: Mean Absolute Percent Error
MOEs	: Measures of Effectiveness
MP	: Milepost
N	: number of segments on a freeway
n	: the sample size
O/D	: Origin/Destination
O_i	: the observation i of field measurement
$Q_i(k)$	: the mean flow rate of freeway link i during interval k
$q_i(k)$	: the volume entering link i+1 from link i during interval k
$R_i(k)$	: the metering rate for an on ramp of link i during interval k
$R_i^{\min}(k)$	: the minimum metering rate for on-ramp i during time interval k
$R_i^{\max}(k)$	: the maximum metering rate for on-ramp i during time interval k
RMSE	: Root Mean Square Error
S_i	: the observation i of simulation output
$S_i(k)$	: the mean speed of link i during interval k
SPSA	: Simultaneous Perturbation Stochastic Approximation

T	: the duration of a time interval
TSM	: Transportation Systems Management
TTT	: Total Traffic Throughput
t	: the acceleration time from the ramp meter to the on-ramp gore
V_t	: the average speed of vehicles on the mainline at time t
V_0	: the initial speed of a vehicle released by a ramp meter
y(λ)	: the measurement of **L(λ)**
Z	: a large positive number
$\alpha_i(k)$	: the weight parameter representing the interaction between flows of links i and i+1 during interval k
β	: non-negative coefficients in SPSA
γ	: non-negative coefficients in SPSA
δ_i^{on}	: the on-ramp parameter (= 1 if an on-ramp of link i exists, otherwise = 0)
δ_i^{off}	: the on-ramp parameter (= 1 if an off-ramp of link i exists, otherwise = 0)
$\theta_i(k)$	: the turning percentage of traffic to the off ramp of link i during interval k
λ	: the mean arrival rate (vehicles per hour)
$\hat{\lambda}_0$	: the initial guess of the optimal **λ**
$\overset{*}{\lambda}_h$	: the optimal solution of **λ** (at the iteration h)
$\hat{\lambda}_{h+1}$	: the estimate of **λ** during the (h+1)th iteration
μ	: the metering rate (vehicles per hour)
ρ	: the ratio of vehicle mean arrival rate and the metering rate (λ / μ)
$\rho_i(k)$	: the density of link i during time interval k
$\mathbf{\Delta}_h$	: random simultaneous perturbation vector during the hth iteration
$\mathbf{\Delta}_{hi}$	: the ith component of the $\mathbf{\Delta}_h$ vector

INTRODUCTION

Problem Statement

Urban freeways often suffer heavy congestion during peak hours, in which capacities decrease and delays increase, and thus the level of service deteriorates. Moreover, the congestion may cause side-wipe and rear-end types of accidents that are associated with the disturbed traffic flow due to merging traffic from ramps. Ramp metering control is regarded as one of most effective freeway traffic management strategies for alleviating congestion. [25,36] Currently, there is no ramp meter operating in New Jersey. The overall goal of this project is to evaluate the potential use of ramp metering control and its effectiveness on Route I-80, one of the most heavily used corridor in New Jersey. Simulation approach is applied in the study to assess the developed dynamic multi-ramp metering control strategy and Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm. Also the potential benefits of implementing ramp metering on the study site are analyzed.

Technical Background

Ramp metering provides a mechanism to control the rate of traffic entering the freeway. By releasing traffic from entering ramps to freeways in measured or regulated amounts, a single vehicle or a small group of vehicles can smoothly squeeze into gaps in the mainline traffic stream. Metering control can be pre-timed, allowing vehicles to enter the freeway every few seconds, or traffic responsive, based on the real-time traffic information (e.g., gaps, speeds, occupancies and queues) collected from the freeway and ramps. Thus, the contracted turbulence in the mainline traffic stream caused by merging flows can be reduced.

As an effective freeway traffic management method, ramp metering control has been discussed for more than four decades. During which, many control strategies varying from the simplest pre-timed metering to the traffic responsive (real-time) metering, have been developed and examined. Also, there have been many efforts in optimizing metering rates for individual and/or a set of ramps. However, little research has been done on quantifying the benefit of ramp metering, while considering the impact of short ramps to both local streets and freeways. Therefore, designing an effective metering control strategy subject to limited storage on ramps is one of the objectives in this study.

Existing Systems

In 1963, ramp metering was first installed in Chicago. Currently, over 2100 meters are deployed on over 2000 miles of freeways in the USA. Many new or reconstructed roadways were designed to use ramp meters as a component of their traffic management systems. A list of existing ramp metering sites and the corresponding measures of effectiveness (MOEs) in the evaluation are summarized in Table 1.1. [36] Various MOEs were used to evaluate the benefit of ramp metering in freeway systems. Among them, speed, traffic volume, travel time, accident rate, and density were most widely used (e.g., the freeways in Denver, CO; Detroit, MI; Long Island, NY; Los Angeles, CA; Minneapolis, MN; Portland, OR; San Diego, CA; and Seattle, WA).

Benefits of Ramp Metering Control

In many studies, the purpose of utilizing ramp metering was the avoidance of flow breakdown on the freeway. To meet this goal, the capacity and demand of each freeway segment were estimated, and then metering rates were imposed such that the freeway could operate with less congestion. This process was rather straightforward and was described elsewhere in the literature. [22] According to the practice discussed in several previous studies, [See references 4, 11, 20, 28, and 36] appropriate implementation of ramp metering control significantly improved traffic operations, particularly in preventing stop-and-go and erratic traffic conditions and balancing demand distributions on the mainline. Such improvements were achieved by allowing ramp traffic to take advantage of gaps in the mainline traffic stream instead of merging with platoons to interrupt the congested traffic flow. The benefit of metering control was classified into various categories listed below: (1) maintaining freeway capacity, (2) maximizing throughput, (3) increasing travel speed, (4) decreasing travel time, and (5) reducing auto emissions and accidents due to a smoother mainline traffic flow. [4,11,36]

Table 1.1 Existing Ramp Metering Sites

Location	Freeway System	Miles Covered	# of Meters	MOEs for Evaluation
Arlington, VA	I-95, I-66	32	26	NA
Chicago, IL	I-90, I-94,I-290, I-57	136	109	NA
Denver, CO	I-25, I-70, I-270, I-225, US-6	NA	28	Average speed, volume, travel time, accident rate
Detroit, MI	I-94	32	49	Average speed, volume, density
Long Island, NY	Long Island Expressway	35	75	Average speed, travel time, throughout, accident rate
Los Angeles, CA	I-5, I-105, I-110	700	808	Delay, accident rate
Milwaukee, WI	I-94, I-43, I-894, I-794, US-45	32	43	NA
Minneapolis, MN	I-35, I-94, I-394, I-494, I-694, SR- 169, SR-62 etc.	160	367	Average speed, volume, accident rate, fuel consumption
Phoenix, AR	I-10, I-17, US-60	200	93	NA
Portland, OR	I-5	6	58	Average speed, fuel consumption, accident rate
San Diego, CA	I-8	126	134	Average speed, volume
Seattle, WA	I-5, I-90, SR-520	NA	54	Volume, travel time

As discussed in a report developed by Minnesota DOT,[28] ramp metering operations in several metropolitan areas (e.g., Minneapolis, MN; San Diego, CA; Seattle, WA; and Denver, CO) demonstrated that the freeway throughput of the metered sections during peak period increased by 17% to 25%, while the throughput of the entire highway systems increased by 5% to 6%. In a survey conducted by Piotrowicz et al.[36] it was found that the mainline speed increased by 16% to 62%, while the number of accidents reduced by 24% to 50%. In general, the average speed increased by 29% after performing ramp metering control. Even considering ramp delays, the average speed was found to increase by 20%.

Traffic congestion can be categorized into recurrent and non-recurrent congestion. Recurrent congestion is predictable. It occurs while traffic density is high and speed is low, such as peak hours. Unlike recurrent congestion, non-recurrent congestion caused by incidents and debris, is quite difficult to predict. Although ramp meters are primarily designed to regulate the volume of entering traffic and reduce the impact of recurrent congestion, more advanced systems can also quickly respond to non-recurrent congestion by controlling the traffic flow in the vicinity of the bottleneck[1]. A previous study [28] indicated that there was an average of 20 minute reduction in response time for incidents in the corridors with ramp metering.

Ramp metering has been considered as one of the most effective methods to improve freeway operations; it may, however, alter the volume of traffic flow entering the metered ramps. Due to the delays experienced by travelers waiting at metering sites, a portion of ramp flow might shift to other freeway entries, or adjacent arterials and surface streets where consume less travel time to reach their destinations. According to previous studies, [8,25,48] the majority of the diverted trips were short trips (e.g., traveling only one or two freeway interchanges) since their waiting times spent at the metered ramps were proportionally greater than that of long trips. Some critics are concerned that ramp metering control might favor freeway operations at the expense of the adjacent surface streets with increasing congestion.

Extensive evaluation of existing metering systems was conducted, and the impact of potential diversion of freeway trips was also analyzed by Piotrowicz, et al. [36] Criteria used in the evaluation included travel distance and time, queue length, and delay at metering sites while considering the availability of alternate routes. It was found that there was no significant traffic diversion from freeways to adjacent alternate routes in Portland, Los Angeles, Seattle, Detroit, Denver, Northern Virginia, Chicago and San Jose, where ramp meters were operated. Also, freeway systems with metered ramps seldom broke down in peak periods even if traffic volume exceeded 2,000 vehicles per hour per lane (vphpl). In addition, it was found that diverting short trips from congested ramps to other under-utilized ramps or alternate routes might be desirable to alleviate congestion in both freeways and parallel arterials/streets.

However, the process of quantifying the benefit of ramp metering control is more difficult. Reduction in delay is often considered as the primary benefit of ramp metering control. Nevertheless, changing of total throughput and impacts on fuel

[1] According to Wattleworth and Berry (1965), a bottleneck is a location where the capacity is lower than the demand. A bottleneck can either be permanent (geometric) such as bridges and tunnels, or temporary, such as peak-hour operations.

consumption, emissions, and safety may also be the beneficial components. In this project, the benefits including the increased throughput and decreased delay after implementing ramp metering control strategies are analyzed.

Project Objectives

Based on the overall goal of the project, the objectives in this study include:

1. *Evaluate the effects of "short ramps" on local traffic congestion (e.g., delays and accidents)*. Short ramps are not purely referred to those ramps short of physical storage area but depend on both storage area and the queue incurred by the entering flow.

2. *Develop a methodology for evaluating freeways with both un-metered ramp and alternative ramp metering control systems.* A simulation approach, rather than actual field studies, will be used in the evaluation, because simulation can efficiently experiment different metering control systems easily and generate various MOEs (e.g., total travel time and queuing delays) adequately.

3. *Develop a real-time multiple-ramp metering control system.* A real-time metering control system will be developed to capture the dynamic traffic characteristics. Also, an effective solution algorithm will be developed for the control system to determine optimal metering rates in real-time. The algorithm will focus on optimizing ramp metering rates rather than the coordination with local surface traffic control systems.

4. *Develop procedures for quantifying benefits of ramp metering control.* The procedures developed in this study will focus on quantifying benefits of ramp metering control under recurrent congestion during peak periods on a daily basis. Total throughput and delay are selected as performance for this analysis indicators.

Organization

This project report is organized into seven parts. In INTRODUCTION, the background of ramp metering control is described and the research objectives are specified. LITERATURE REVIEW AND CURRENT PRACTICE summarizes findings from previous studies. A number of ramp metering control strategies and models are reviewed, while the requirements and guidelines for implementing ramp metering control on freeway and ramps are discussed. The collected data for this project are described in DATA COLLECTION, and then the developed simulation model based on the collected data is discussed in SIMULATION NETWORK MODELING. In EVALUATION OF RAMP METERING CONTROL, ramp meter location, ramp storage capacity and benefits under ramp metering control strategies are analyzed. The potential metered ramps for this study are identified in the part. The development of a dynamic ramp metering control model with simultaneous perturbation stochastic approximation (SPSA) algorithm is discussed in DYNAMIC MULTI-RAMP METERING CONTROL, while the evaluation of the developed real-time ramp metering control model is summarized. Finally, CONCLUSIONS AND RECOMMENDATIONS are presented.

LITERATURE REVIEW AND CURRENT PRACTICE

There is a great deal of skepticism as to whether ramp metering control can be successfully implemented on New Jersey freeways. Previous studies [3,25,36] addressed the success of metering control systems on freeways in various cities and discussed how those systems could be potentially applied. However, very broad guidelines with limited recommended practices were discussed and no national standards were developed. The major reason was that control decisions were usually determined by local traffic and geometric conditions.

MUTCD [15] stated that the installation of ramp meters might be justified when the average delay of a subject freeway corridor was expected to be reduced. MUTCD also suggested that a thorough analysis of the geometric and traffic conditions of the freeway corridor should be conducted to determine whether ramp metering control was feasible. It was generally agreed among various highway authorities that the potential metering sites were those having poor traffic conditions (e.g., low speeds of 30-48 mph, low volumes of 1200-1500 vphpl) or higher rates of merging accidents.[25] In a study conducted by Taylor and Meldrum, [46,47] it was suggested that the potential metering sites should be the places where the implementation of ramp metering control could prevent flow breakdown. Besides, special consideration should be given to the upper and lower bounds of metering rates, locations of signals and signs, and ramp geometry. Requirements for developing a ramp metering control system are discussed from pages 7 to 16. Ramp metering control strategies and models developed in previous studies have been systematically reviewed and discussed from pages 16 to 25, while the review of simultaneous perturbation stochastic approximation and a summary is present from pages 25 to 27.

General Requirements

In this section, the general requirements of metering alternatives, constraints of metering rates, signs and signals, and ramp geometry are discussed below.

Metering Alternatives

According to the way of releasing vehicles, two metering control alternatives were generally discussed: one-by-one metering and platoon metering control. [25] One-by-one metering control only allows releasing a single vehicle per lane per cycle. Since the merging condition of one vehicle is smoother than that of a platoon of vehicles, one-by-one metering control can greatly reduce the interference of ramp traffic to the traffic on the mainline and the associated accidents. Thus, one-by-one metering control was preferred in many places, where especially a bottleneck was in the vicinity of an on-ramp gore. One-by-one metering control was thus determined to be evaluated in this study.

Platoon metering control, on the other hand, allows releasing two or more vehicles per cycle. This can be achieved either by increasing the duration of green time for the metered ramps, or releasing two vehicles per lane per cycle. The platoon metering control is designed to handle higher ramp metering rates. Based on the operational experience on two-lane ramps, platoon metering control worked well and was preferred by practitioners. For one-lane ramps, however, platoon metering requires a longer cycle that may induce the uncertainty of driver behavior and thus increase the probability of interrupting the mainline traffic. Thus, platoon metering control should be chosen with caution.

Upper and Lower Bounds of Metering Rates

A very general rule for choosing the upper and lower bounds of metering rates was recommended by traffic agencies and practitioners. [4,28] Usually, it might take several weeks or even months to calibrate the bounds for specific systems based on local traffic operations.

Poitrowicz, et al. [36] found that drivers might lose patience to wait for more than 15 seconds before a ramp meter. Beyond 15 seconds, the number of violations increased significantly. While maintaining an acceptable queue length on a ramp, the ramp storage constraint must be considered. The minimum metering rate was determined based on the maximum acceptable queue length. The mainline congestion could be mitigated with appropriate ramp metering control. Considering short ramps, Maher, et al. [25] developed a method to estimate the minimum metering rate subject to the constraint of the storage capacity and the demand of the ramp. Practically, the minimum metering rate was about 240 vphpl (= 15 seconds/veh), and the maximum metering rate for one-by-one metering varied from 600 - 900 vphpl. [5] The metering rate of 900 vphpl was based on a cycle length of 4 seconds (2 seconds each for green and red light, respectively). For platoon metering control, the maximum metering rate could be increased to 1200 vphpl.

Signals and Signs

Ramp meters should meet all design specifications for control signals. Signal heads of a ramp meter at can be either two-colored (red/green) or three-colored (red/green/amber), which was discussed by MUTCD in 2000. A two-head signal is suggested because it provides a backup in case of malfunction or damage. The signal can be located on left-hand side only or on both sides of a ramp for best visibility. Highway authorities are suggested to choose adequate signal type according to local design regulations, and ensure the consistency throughout the entire system.

Even if the public is well informed, drivers may not expect to stop before ramp signals. Therefore, the advance-warning signs of downstream ramp meters are required to alert drivers. The commonly used warning signs are blank or static enhanced with flashing lights. Many states have their own standards for the warning signs. For example, CALTRAN suggested to use strobe lights in the red lens to reduce accidents at metered ramps. The location of advance-warning signs usually depends on ramp geometry and sight distance. Moreover, supplementary signs with the legend "**STOP HERE ON RED"** or "**WAIT HERE FOR GREEN"** are commonly used to inform drivers of the existence of a ramp meter.

Ramp Geometry

The ramp geometric characteristics (e.g., the adequate sight distance, acceleration distance, and availability of storage space) should be carefully investigated before implementing ramp meters. In order to avoid vehicles spillback onto local streets, adequate ramp storage is required. Otherwise, a better traffic diversion plan should be applied for relieving local traffic congestion. California DOT [4] used an arrival-discharge chart, while Minnesota DOT [28] used a rule-of-thumb for estimating queue length that was 5-10% of the pre-metered peak hour volume. The estimated queue length could then be used for designing enough storage spaces on metered ramps.

For increasing the size of ramp storage, a commonly used technique was to increase the number of lanes on ramps. Minnesota DOT [28] required all metered ramps to have at least two lanes before the ramp meter. In San Diego, a portion of the surface street was used to store vehicles, which required channelization and signal timing adjustment on the adjacent streets. Occasionally, the queue exceeded the storage capacity because of stochastic vehicles arrivals. In order to avoid this situation, an alarm would be triggered when a long queue was detected before spillback occurred over the ramp entrance. The metering rate should be increased to discharge more vehicles. In addition to the criteria mentioned above, the issues of public acceptance, enforcement requirements/regulation and availability of suitable alternate surface routes should be considered before implementing ramp metering control. [15,25,36]

Technical Requirements

Freeway surveillance systems and their elements, ramp metering controller and constraints for ramp metering control systems are discussed as follows.

<u>Freeway Surveillance Systems</u>

While applying ramp metering control on a freeway network, various types of data (e.g., volume, speed and occupancy) are required for determining appropriate metering rates. Most freeway surveillance systems can provide these information through the connection between detectors installed on freeways/ramps and communication devices (e.g., data transmission and processing devices). Considering the rapid growth in solid-state electronics and computer communication technologies, freeway surveillance systems nowadays have demonstrated desirable performance. A good surveillance system should be reliable and easily maintained.

As a primary component of a surveillance system, detectors play an important role in collecting traffic data. The commonly used detectors in freeway surveillance systems are classified two types (e.g., the embedded detector and the non-intrusive detector) listed in Table 2.1. [16]

Table 2.1 Summary of Traffic Detectors

Detector type	Description	Advantages	Disadvantages
Embedded Inductive Loop	Coil of cables embedded in pavement surface, which recognize the presence of vehicles through minute changes in electrical voltage caused by passing of vehicles.	Flexible Design. Wide range of application. Provides basic traffic parameters (e.g., vehicle counts and occupancy).	Requires pavement cuts to install. Subject to stress of traffic. Frequent maintenance requires lane closure.
Magneto-meter	Small-cylinders contain sensor coils which operate similar to inductive loops. Developed as alternative to loop detector in special situations.	Used in situations where loops are not feasible. (e.g. bridge decks) Less susceptible than loops to stress of traffic	Small detection zone. Typically used to provide only vehicle counts and occupancy.
Non-Intrusive Microwave Radar	Transmits electromagnetic wave to vehicles on roadway. Calculate traffic parameters by measuring the feedback signal frequency.	Generally insensitive to weather conditions. Provides day and night operation.	May lock on to the strongest signal (e.g., large truck.)
Infrared	Active infrared detectors transmit thermal radiation, while passive infrared detectors only measure the changes in thermal radiation that vehicles emit.	Active detectors emit narrow beam allowing for accurate determination of vehicle position. Provides most basic traffic parameters during day and night operation.	Operation affected by precipitation (e.g., snow and fog). Difficult in maintaining alignment on vibrating structures.
Ultrasonic	Transmits sound waves at frequency ranging 20 and 200 kHz. Detects vehicles by measuring return waves.	Provides most basic traffic parameters.	Weather conditions (e.g., temperature, humidity, air turbulence) can affect performance.
Acoustic	Uses microphones and signal processing technology to detect sounds associated with vehicles.	Generally insensitive to weather conditions. Provides day and night operation.	Relatively new technology for traffic surveillance.
Video Image Processing	Video image processors receive information from video cameras and use algorithms to process the video image input.	Provides basic traffic parameters. Provides wide-area detection.	Performance may be negatively affected by harsh weather, shadows, and dim lighting. High installation and maintenance cost.

According to the functions for the use of ramp metering control, detectors can be classified into (1) mainline, (2) merging, (3) passage, (4) demand, and (5) queue detectors, as shown in Figure 2.1. Note that all detectors in the figure are shown by loop detectors, while functional equivalent detectors, such as magnetometer, sonic or other detectors can be applied to collect more reliable information (e.g., speed, occupancy, volume, and queue status).

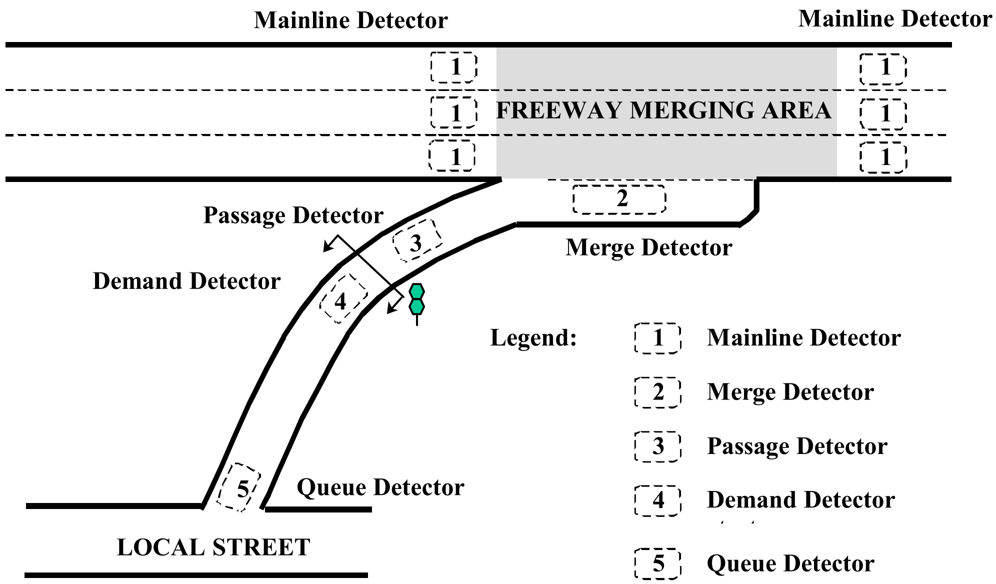

Figure 2.1 - Configuration of a Typical Metering Ramp

Mainline Detectors

Mainline detectors are installed on the freeway mainline, which are usually located either prior or after the merge area as shown in Figure 2.1. Information collected from the detectors includes flow rates, speeds and occupancies. Sometimes two sets of mainline detectors are jointly used for estimating the number of vehicles within the merging area.

Merge Detectors

Merge detectors are installed after the on-ramp gore to detect the number of vehicles merging into the mainline traffic stream and whether the merging area is jamed. When the jam occurs, the controller may hold the ramp signal in red to avoid stacking on the merging area.

Passage Detectors

Passage detectors are installed just beyond the stop bar of the metering signal (e.g., 8 ft), which can register vehicles released during each green interval. As soon as the anticipated number of vehicles passing the stop bar is sensed, the green signal shifts to the red. Sometimes passage detectors are served as both passage and merge detectors, but with less accuracy. [25]

Demand Detectors

Demand detectors are installed with sufficient length before the stop bar of the metering signal (e.g., 18 ft), whose function is to register the presence of vehicles waiting for passage.

Queue Detectors

Queue detectors are usually installed at the entrance of an on-ramp, or sometimes at the adjacent local street. The main function of queue detectors is to detect the queue length that may spill-back onto the local street and report this information to the controller. Thus, adequate control actions can be taken to avoid queuing vehicles blocking the local street.

Note that the determination of detector locations is highly dependent on the type of metering control (e.g., pre-timed, traffic responsive) and the geometric condition of the study site (e.g., length of auxiliary lane, storage capacity, weaving length, etc.). Characteristics of various types of detectors are summarized in Table 2.2.

Table 2.2 Characteristics of Detectors for Metering Control

Type of Metering Detector	Approximate Dimensions (ft)	Traffic Parameters Measured
Mainline	6×6	Speed, Occupancy, Vehicle Counts
Merge	40×6	Occupancy
Passage	6×6	Vehicle Counts
Demand	Two 6×6 loops or one 15×6 loop	Occupancy
Queue	6×6	Occupancy

Ramp Metering Controllers

The ramp metering controller is responsible for determining metering rates/cycles through implementing control strategies and tactics. For pre-timed controllers (e.g., dial-and-stepped-cam controller, digital controller), metering rates or intervals of red, yellow and green lights can be set up either with a time clock or by remote control. The duration of each metering interval determined by such a controller corresponds only to recurrent traffic conditions. Therefore, the major disadvantage of the pre-timed controller is its less ability to respond to non-recurrent traffic conditions and significant traffic variation within a time period. For centralized controllers, the timing and control operations can be determined by computer software that optimizes metering rates based on extensive traffic information collected from detectors. The centralized controller can be surrogated by a backup pre-timed controller that initializes pre-specified metering rates in case of computer failure during metering periods. The centralized controller can dynamic change signal timings to adapt to the change of traffic conditions.

Constraints of Ramp Metering Control Systems

Several constraints were usually considered in the application of ramp metering control to ensure that the solution metering rates were feasible or workable at individual ramps. These constraints include: (1) the upper and lower bounds of metering rates allowed for the metered ramp, (2) the demand-capacity restriction at the vicinity of the metered ramp, and (3) the storage capacities of the metered ramps, which are described below.

Upper and Lower Bounds of Metering Rates

According to the literature review conducted on pages 8 and 9, traffic engineers determined the highest and lowest metering rates based on practical consideration. For one-by-one metering control, the minimum metering rate was 240 vehicles per hour per lane (vphpl), since a rate lower than that might cause a high violation rate. On the other hand, drivers needed at least 4 seconds to stop, response to the ramp signal, and prepare to merge into the mainline. The maximum metering rate for one-by-one metering control was 900 vphpl. [25,36]

The appropriate metering rates were suggested to be within the feasible range, between the upper and lower bounds of metering rates of 900 and 240 vphpl, respectively. Assume that a general freeway segment has N links, numbered from 1 through N from the upstream end to the downstream end of the freeway. The metering rate $R_j(t)$ for the metered ramp on the j^{th} link at time *t* (see Figure 2.2) should be greater than the minimum allowable metering rate L_j and less than the maximum allowable metering rate U_j. Thus,

$$L_j \le R_j(t) \le U_j \qquad \text{for } j = 1, \ldots, N \qquad (1)$$

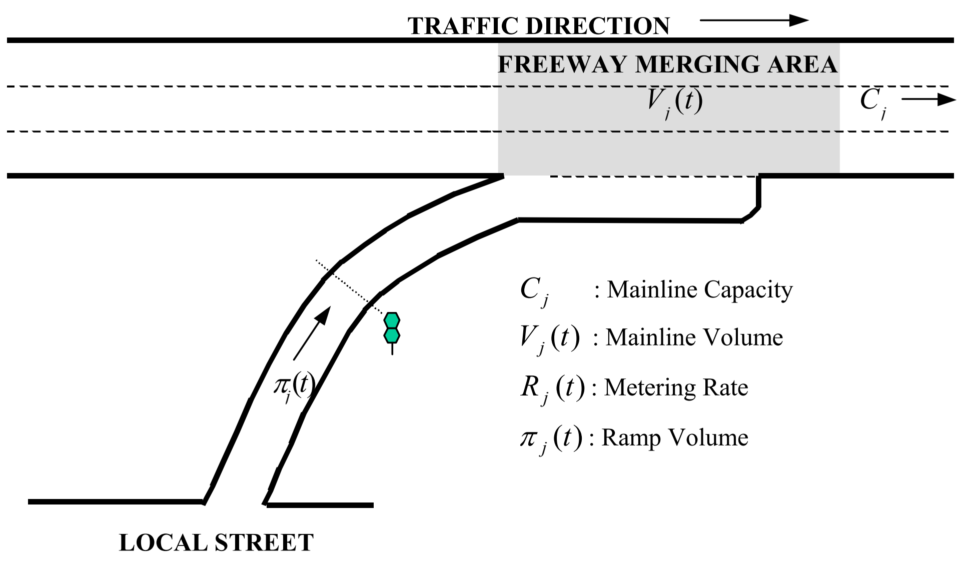

Figure 2.2 - Configuration of a Ramp Junction

Capacity Constraints

The capacity constraints discussed here are used to determine metering rates if the freeway capacity C_j and the entering volume $V_j(t)$ at time *t* can be estimated. The metering rate $R_j(t)$ should be less than or equal to the difference between C_j and $V_j(t)$. Thus ,

$$R_j(t) \le C_j - V_j(t) \qquad (j = 1, \ldots, N) \qquad (2)$$

In Eq. 2, if $V_j(t)$ approaches C_j, the metering rate decreases and congestion may occur in the ramp junction. In such a situation, the metering rate should be the minimum metering rate (e.g., 240 vphpl) or less to secure that the traffic flow is always less than the mainline capacity.

Queue Constraints

Queue constraints are used to prevent the congestion caused by queuing vehicles spill-back from the metered ramp to the local street. Usually, short ramps have limited storage areas because of physical restriction (e.g., lane-mile) or large entry demand. Therefore, the metering rate should be optimized subject to the relationship between the ramp storage and the entry flow into the metered ramp.

The queue detector installed at the entrance of the on-ramp is functioned to monitor the queue length and the duration that the detector has been occupied. If the duration is greater than a pre-specified threshold duration, the metering rate will be increased to quickly discharge the queue.[25,36] In practice, several threshold durations are specified to invoke different metering rates. A solid-green state will be given when a long queue occurs.

Ramp Metering Control Strategies

Over the past four decades, various ramp metering control strategies have been studied. These strategies were applied to determine the optimal metering rates and achieve certain objectives shown in Table 2.3. In this table, the objectives vary from minimizing travel time, delay, and number of diversion vehicles to maximizing entry volume and throughput. Despite of the diversity of these objectives, they can be categorized into two categories: (1) maximizing total input and (2) maximizing total output (capacity utilization). The theoretical proof of the equivalence for the objectives under the same category can be found in previous studies conducted by Wattleworth, et al. [49,50] and Masher, et al. [25]

Table 2.3 Objectives of Ramp Metering Strategies

Category	Objectives	Unit(s)
Maximize total input	Minimize total travel time	Vehicle-hour, person-hour
	Minimize overall queuing delay	Vehicle-hour, person-hour
	Maximize total input volume	Vehicle, person
	Minimize total diversion	Vehicle, person
Maximize total output	Maximize total mainline volume given a level of service	Vehicle, person
	Maximize total throughput	Vehicle-mile, person-mile

In general, ramp metering control strategies can be classified into four categories: (1) Pre-timed, (2) Local Traffic Responsive, (3) System-wide, and (4) Integrated System Control. They are discussed next.

Pre-timed Control Strategy

One of the pioneer ramp metering control strategies is pre-timed control. The metering rate is determined by analyzing historical volume-capacity conditions during a specific time period for the target ramp. The pre-timed control provides basic function of breaking up platoons by setting an upper flow rates at the metered ramp. Although such a strategy can not effectively respond to variations in traffic conditions over time (only historical average volumes for a mainline and on-ramp are considered), it can often be implemented as initial operating strategy until individual ramps can be incorporated into a traffic responsive system. Pre-timed control can be implemented on a number of ramps to reduce accidents [(37)] and travel times [(23)].

Local Traffic Responsive Control Strategy

The local traffic responsive control strategy determines metering rates for single or a set of individual ramps. The metered ramps are considered independent rather than interconnected. Unlike pre-timed control, local traffic responsive control determines metering rates based on measured traffic conditions collected from traffic surveillance devices (e.g., detectors on the ramp and mainline). The commonly used local traffic responsive strategies are demand-capacity, occupancy, gap acceptance and speed control. (See references 14, 19, 35, and 51) Among those, demand-capacity and occupancy-based strategies are operated similarly. In both, the metering rates are based on the difference between the mainline capacity (or the volume for a desired service level) immediately downstream of the ramp and the upstream traffic volume. However, occupancy-based control estimates traffic volume based on detected occupancy instead of measuring the volume directly. For gap-acceptance and speed-control, the gap at the merging area and the upstream speed are detected respectively and applied to determine the proper metering rates.

Although local traffic-responsive control strategies do respond to actual traffic conditions, they can not perform very well especially for the upstream metered ramps of a bottleneck. It is because that the downstream congestion cannot be detected until the shock wave stacks back the metered ramp. The existing practices are ALINEA in Paris, France (34) and in Austin, Texas (36).

System-wide Control Strategy

System-wide control strategies refer to the dynamic control on a series of on-ramps. The major feature of the system-wide control is that all metered ramps are considered interconnected. Therefore, the metering rate at a ramp is also influenced by traffic conditions at other metered locations. The system-wide control determines metering rates from both overall system and local capacity constraints, and real-time traffic measurements. The strategy usually leads to non-linear optimization programming governed under centralized computer systems. Existing practices are METALINE implemented in Paris, France (32,33), Seattle, Washington, and Denver, Colorado (36,46,47).

Integrated System Control Strategy

Recently, the concept of integrated system control has attracted considerable interest (7). The integrated system control coordinates not only the freeways and ramps, but also the arterials and local streets to achieve desirable corridor wide performances (e.g., total travel time and delay). The ramp meters and arterial traffic signals/signs can be jointly optimized in response of real-time traffic conditions. The potential advantage of the integrated system control is that the corridor wide surveillance and control can benefit travelers on both freeways and arterials. Projects toward developing and implementing such integrated control are underway in Seattle, Washington. [21,22]

Ramp Metering Control Models

Various models have been developed and experimented in real-world freeways or in a simulation environment. According to different optimization methods applied for the developed ramp metering control models, they are categorized into four groups: (1) Pre-timed Linear Programming Models, (2) Local Traffic Responsive Models, (3) System-wide Non-linear Programming Models, and (4) Emerging Large-scale Heuristic Models.

Pre-timed Linear Programming (LP) Models

Pre-timed linear programming models are static models that search the optimal combination of metering rates for single or a set of ramps. Such models aims at sending vehicles as many as possible onto the freeway subject to the demand and capacity constraints on each freeway segment. Because the availability of LP software packages and only historical data were available, the LP models were fairly simple to be implemented. [25] However, such models with pre-specified metering rates could not respond to significant variation traffic stream over a time period.

Wattleworth and Berry [50] analyzed theoretical consideration of the ramp metering control during peak periods. In that study, the objective functions (i.e., total travel time and system output) of the metering control were developed, while the traffic measurements as well as the locations of the detectors needed for the control were discussed. An LP model was formulated. The pre-timed metering rates were optimized by maximizing the system output (total exiting volume via the mainline exit and off ramps). Two linear constraints were considered in the model: the bottleneck capacity constraint and the upper bound of metering rate constraint. A segment of Congress Street Expressway in Chicago was analyzed. The optimal ramp metering rates were determined based on assumed O/D demand information. However, the queue constraints on the metered ramps were not considered.

A similar LP model was developed by Wattleworth. [49] The total input to the freeway system (including mainline and on-ramps) was maximized for a pre-timed metering system, while the constraints of bottleneck capacity, the upper bound metering rate, and the queue length were considered. He found that metering control would be one of the most effective ways to maintain stable traffic flow condition on a congested freeway network. Moreover, he concluded that the adequate ramp storage area should be designed to keep adjacent streets from being adversely impacted. Later, Papageorgiou [29] further enhanced Wattleworth's LP model, considering time-varying traffic fluctuations of the mainline. However, the mainline volume could only change at a pre-specified frequency (e.g., twice during the peak period), which was still incapable to respond to situations with significant traffic variations.

Chen, et al. [9] developed a metering control model that maximized average freeway throughout when peak demand exceeded freeway capacity. In that model, the ramp metering rates were optimized subject to the upper bound metering rate and density constraints. The Greenshield's model was applied to define the speed and density of the studied freeway.

Local Traffic Responsive Models

With local traffic responsive models, ramp metering rates were optimized based on real-time traffic conditions. The pioneer research on local traffic responsive models was conducted by Drew [14] and Wiener, et al. [51] The statistical gap-acceptance models were used to analyze vehicle movements in a merging area. Their models could be applied into a traffic responsive controller to break up vehicle platoons into single or a smaller group of vehicles merging into the mainline traffic stream according to the sizes of detected gaps.

Drew [14] studied the merging behavior on Gulf Freeway in Houston, Texas. Factors affecting the critical gap (acceptable gap by half of the drivers when merging with the mainline) were identified, while the critical gaps were found to follow gamma distribution. The vehicle merging delays and the average queue length of were formulated by assuming that the vehicle headways on the mainline followed Erlang distributions. In that study, the ramp metering rate was optimized based on the queue length and pre-specified critical gap of the metered ramps.

In a later study conducted by Wiener, et al.,[51] the gap-acceptance models were developed to optimize the critical gap through minimizing the expected queue length and wait time for a ramp. The stochastic process of queue diminishing and regeneration on the ramps of Gulf Freeway in Houston was studied. The gap-acceptance models for stationary queue length and wait time were formulated as a function of critical gaps by assuming that vehicle arrivals at ramps followed a Poisson distribution. The optimal metering rates could be adjusted based on detected queue length.

Stephanedes, et al. [44] evaluated a traffic responsive control model for I-35w developed by Minnesota DOT. For each metered ramp, a rate table was developed according to the volume-occupancy thresholds and the corresponding metering rates derived from historical data of the ramp. In real-time operations, the upstream volume and downstream occupancy of the ramp were compared with the thresholds in the rate table, and then the proper metering rate could be identified. The MOEs used for evaluation included the total entry volume and the total delay experienced by vehicles traveling under 45 mph. The results suggested that the rate table should consider the trade-off between the increased capacity and increased delay.

ALINEA, developed by Papageorgiou, et al.,[19,34] was a local occupancy-based metering control strategy and designed through the application of classical feedback control law. Only two measurements, occupancies on the ramp and immediately downstream of the ramp, were used to dynamically adjust the metering rates. ALINEA was tested on the Peripherique Corridor in Paris,[19] while three MOEs (i.e., total travel distance, total travel time and mean speed) were used to assess the efficiency of the control. Although the results were encouraging, the excessive queue length on ramps frequently caused the control overridden with the maximum metering rates in order to discharge the queues.

Banks [2] analyzed ALINEA and found that the linear controller was more effective for regulating non-congested traffic when nonlinearities in traffic behavior were not presented. He developed a local traffic responsive model, within which the metering rate was determined by the difference between the upstream and downstream mainline volumes, while the difference between the actual released volume and metered volume was used to adjust the metering rate dynamically. The model was tested on WB I-8 and WB SR-94 in San Francisco, and the results showed that the model was more applicable when the analyzed freeway had sufficient capacity (e.g., un-congested traffic conditions).

System-wide Non-linear Quadratic Programming Models

In view of the deficiencies of local traffic responsive model (e.g., ramps are considered isolated rather than connected), several system-wide metering control models were developed. (See references 1, 6, 8, 30, 31, 32, and 44) The system-wide models could handle a series of ramps in a traffic responsive schema, while considering the interconnections of traffic conditions between consecutive ramps in real-time. The system-wide models often led to hierarchical non-linear optimization programming carried by centralized computer systems, which processed traffic data, optimized metering rates, and executed the control law through ramp meters in real-time.

System-wide non-linear models were first developed by Yuan, et al. [52] The equivalent traffic demand was formulated as the sum of traffic and queue demand in order to balance the queues on all metered ramps and prevent vehicles spillback onto local streets. A quadratic programming problem was formulated to determine the desirable metering rate by penalizing the deviation from the equivalent traffic demand. In the optimization, three constraints were used: the vehicle conservation constraint[2], the Greenshields' speed-density constraint, and the upper bound metering rate constraint. The model was tested on a hypothetical freeway with only one on-ramp. The results showed that the optimal metering rate could shorten the queue length on the ramp yet without significant reduction of the freeway throughput.

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[2] According to vehicle conservation principle, the change of density over time is proportional to the change of flow rate with respect to position along a freeway segment.

Stephanedes, et al. [44] presented a non-liner metering control model to alleviate congestion during peak periods. In his study, the vehicle conservation and Greenshields' speed-density models were used to describe the traffic flow in a freeway corridor, while the total vehicle travel time was used as the objective function to optimize the metering rates. The optimal ramp metering rates were determined by minimizing the quadratic objective function using a conjugate gradient search method. The model was tested on a hypothetical freeway segment with one on-ramp. The results showed that due to the limitation of the network size, the total travel time was not reduced significantly.

In a real-time traffic control system, the short-term prediction of traffic information (e.g., speed, volume, density, and occupancy) became a necessity to respond to traffic variation effectively [38]. Thus, prediction was proposed as a very important component in system-wide metering control models. Papageorgiou [30] developed a hierarchical decomposition algorithm that could deal with large-scale nonlinear problems including optimization, prediction and control. This algorithm consisted of three functional layers: adaptation layer, optimization layer and direct control layer. The adaptation layer predicted exogenous parameters to the control model, including traffic speed, volume, and occupancy. With the predicted parameters, the optimization layer determined the optimal metering rates for a set of ramps by minimizing the total vehicle travel time. The direct control layer then implemented a local feedback control law to maintain the optimal metering rates for individual ramps despite of various disturbances such as traffic incidents in real-time. The model was tested on a hypothetical freeway network with six on-ramps and six off-ramps.

Later, Papageorgiou, et al. [31] developed three dynamic traffic flow models (e.g., vehicle conservation, volume-density and speed-density models) while considering the impact of weaving movements at ramp junctions. The three nonlinear models were tested using real traffic data collected from the Boulevard Peripherique in Paris. After thorough investigation in mathematical structure, parameter calibration, and sensitivity analysis, the models were integrated with a system-wide ramp metering control model and simulated in Paris (Papageorgious, et al., 1990). In that study, a metering control model METALINE was developed, within which a Linear-Quadratic (LQ) control law was implemented. The simulation results showed that METALINE could be activated earlier before congestion formed at the ramp junction and thus dissolved congestion more effectively than pre-timed control or local control systems, such as ALINEA.

Emerging Large-scale Heuristic Models

Because the system-wide ramp metering models usually involved in rather complex nonlinear optimization techniques, which required considerable computation efforts for obtaining optimal solutions, these models were too time-consuming for real-time implementation. Besides, these models might result in oscillatory metering rates because of the difficulty to describe non-linear and time-varying freeway systems, especially when traffic data were frequently corrupted with noise or transmission errors. Some heuristic ramp metering models were developed to achieve sub-optimal solutions for large-scale freeway systems, (See references 10,18, 27, and 45) which could quickly respond to dynamic traffic conditions in freeway operations and efficiently release ramp vehicles.

Goldstein and Kumar [18] developed a decentralized metering control model to obtain the sub-optimal metering rates for large-scale freeway systems. They argued that the widely used centralized control model might require manipulation on large size matrices, which was fairly time-consuming. In their study, metered ramps were divided into groups with overlapping (e.g., ramps 1, 2, 3 as group 1, ramps 2, 3, 4 as group 2, and ramps 3, 4, 5 as group 3, etc.). The centralized model was transformed using the cascading technique such that a sub-controller could handle the ramps in each group. The decentralized control model needed less time because of the smaller matrix size, yet the traffic conditions in both upstream and downstream ramps were considered. The model was tested by simulating a freeway network in San Diego, California. The results showed that the model could respond to dynamic changes in local traffic conditions much more quickly than the centralized controller, while similar improvement in average speed and delays were achieved.

Chen, et al. [10] developed an expert fuzzy controller for a ramp metering control system near the San Francisco-Oakland Bay Bridge. The objectives of the controller were maximizing system throughput and minimizing adverse impacts on local streets. Seven rules were designed based on expert knowledge from the bridge operators, with the form of IF "freeway condition" THEN "control action". A look-up table was integrated with the seven rules to determine adjusted metering rates under various traffic conditions, ranging from heavily congested to extremely light flow in the rule base. Through fuzzy logic implication, the controller could infer to what degree the condition was true, thus determined metering rates. The simulation results showed that the possible saving percentage in person-hours with the expert fuzzy control was 40%.

McDonnell, et al. [27] presented an evolutionary programming for freeway ramp metering control. The rule-based controller determined metering rates based on upstream, downstream, and adjacent freeway occupancy levels. Evolutionary programming was demonstrated as a viable approach to integrate ramp metering control strategies to alleviate freeway congestion effectively.

Taylor, et al. [45] developed a fuzzy logic model to control multiple ramps in a large-scale freeway network. Seventeen rules, including the five rules for occupancy, four rules for speed coupled with occupancy, six rules for shock waves/acceptable gaps, and two rules for excessive queues, were developed and integrated with FRESIM, a microscopic freeway simulation model developed by FHWA. A simulation of northbound traffic on I-5 in Seattle was conducted, while three MOEs (e.g., total vehicle travel distance, total travel time, and average delay) were evaluated. The simulation results showed that the fuzzy logic control outperformed the Local Metering Model and the Bottleneck Model that were used in the freeway control system in Seattle. The testing results indicated that fuzzy logic control algorithm could achieve lower mainline occupancy and higher throughput than Local Algorithm.[46,47]

Simultaneous Perturbation Stochastic Approximation

Recently, Simultaneous Perturbation Stochastic Approximation (SPSA) has attracted attention from transportation researchers. SPSA is a mathematical algorithm to search the optimization solution, which starts with an initial guess, then update with iterations until approximates the desired result.

SPSA does not rely on direct measurements of the gradient (derivative) of the objective function being optimized, instead, it relies on measurements of the objective function, which avoids the difficulties to obtain detailed modeling information describing the relationship between the parameters to be optimized and the objective function. SPSA is especially efficient in multivariate optimization problems of minimizing or maximizing an objective function dependent on multiple variables. Since there are fewer algorithm coefficients that need to be specified, SPSA will be easier to implement than other stochastic optimization methods. (40,41) SPSA is a powerful method for optimization in challenging nonlinear problems. Theoretical and numerical studies generally shows that SPSA have equal or greater efficiency in terms of the overall cost of the optimization process (42,43). SPSA is quite promising and an easy-to-use optimization algorithm. (24,48)

In this study, SPSA algorithm is proposed to solve the optimization problem in ramp metering control. The detailed SPSA algorithm will be introduced from pages 69 to 73.

Summary

In this part, the general requirements for various ramp metering control systems were discussed, including the freeway surveillance systems, metering controllers and constraints for previous metering control algorithms. The freeway surveillance systems were focused on discussing locations of detectors for metering control. Two types of metering controllers, pre-timed and computer-centralized controllers were described in detail. Three types of constraints associated with ramp metering control, the upper and lower bounds of metering rates, the capacity and the queue constraints. These constraints widely used for both localized and system-wide systems will be critical for developing the real-time ramp metering control in this study.

In this study, several metering control strategies (e.g., pre-timed and traffic responsive) and models will be evaluated, while the potential benefit of ramp metering control for the study site will be discussed. The core concept of the proposed real-time ramp metering control discussed here is to simultaneously capture the dynamic traffic characteristics to ultimately improve corridor-wide traffic operations. An effective algorithm (SPSA) will be developed for determining the optimal and time-varying metering rates.

DATA COLLECTION

This part is organized into three sections. In Site Identification, the location, geometric characteristics and current traffic situation of the study site is described. In Site Visit, the study site with photo pictures and diagrams are displayed. The catalogued and collected data are discussed and summarized in Data Collection.

Site identification

The study site for evaluation of metering control on eastbound I-80 was selected by NJDOT engineers and the research team, which starts from milepost (MP) 29.2 ends at MP 41.1. The site is about 12-mile long, where seven on-ramps and five off-ramps connect the local streets/arterials and the study site. The configuration of the study site is shown on Figure 3.1.

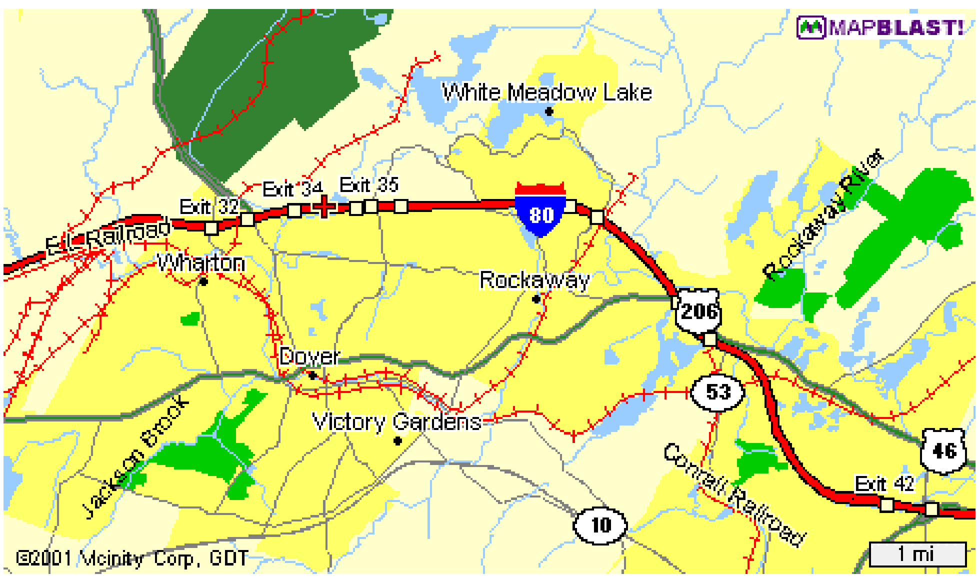

Figure 3.1 - Map of the Study Site

Though there was no ramp metering control on freeways in New Jersey, the recommended site was selected based on the availability of data and compatibility with control strategies to be tested. Most of the data on this study site were provided by NJDOT engineers and will be used to develop a simulation model.

Site Visit

Several field trips were made, and photos were taken on September 13, 1999 to have a general overview of local traffic conditions. The collected geometric and traffic conditions are shown in Figures 3.2 through 3.9. We found that the traffic on westbound I-80 was very light during morning peak period. The heavy congestion was observed on eastbound I-80, and the heaviest congestion occurred at the ramp junction of Route 513/Hibernia Avenue. Figure 3.5 presents heavy traffic at the ramp junction of Route 661 & Mount Hope, while traffic from two ramps at the ramp junction of Route 615 & Howard Boulevard could be observed (see Figures 3.6 and 3.7). Figures 3.8 and 3.9 show the geometric and links/nodes diagrams of the study site, respectively.

Figure 3.2 - Mainline I-80 (Route 513/Hibernia Avenue)

Figure 3.3 - Ramp 375 on I-80 (Route 513/Hibernia Avenue)

Figure 3.4 - Ramp 376 on I-80 (Route 513/Hibernia Avenue)

Figure 3.5 - Ramp 356 on I-80 (Route 661/Mount Hope)

Figure 3.6 - Ramp 306 on I-80 (Route 615/Howard Boulevard)

Figure 3.7 - Ramp 307 on I-80 (Route 615/Howard Boulevard)

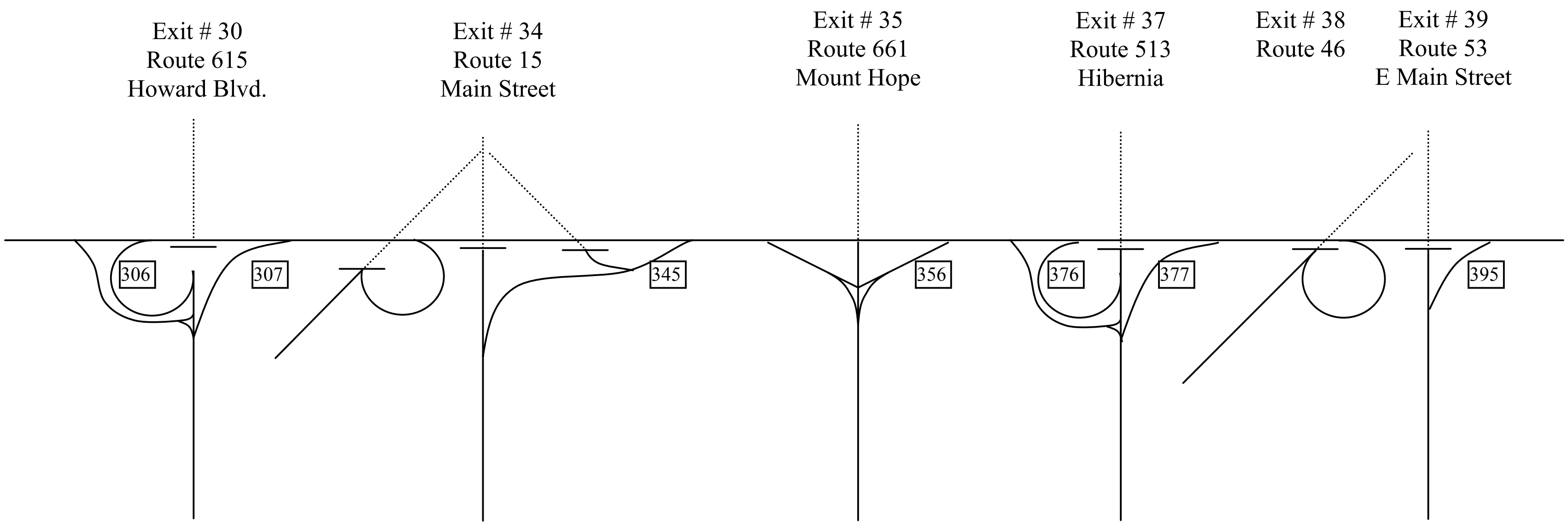

Figure 3.8 - Geometric Diagram of Eastbound I-80 Mileposts 29.2 - 41.1

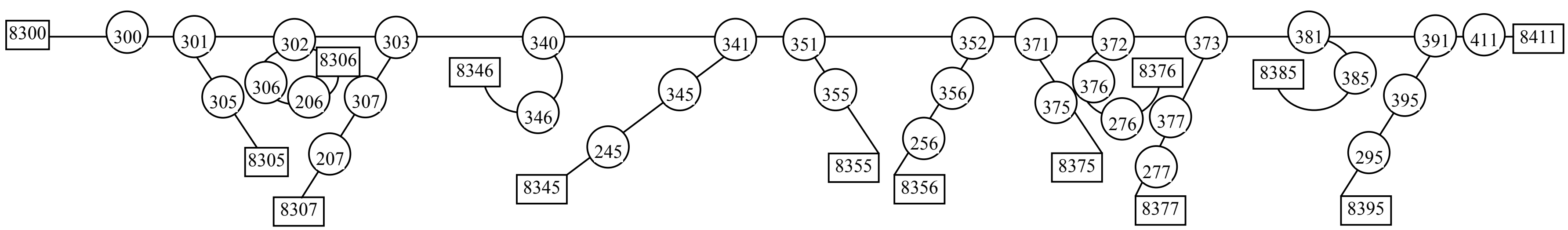

Figure 3.9 - Link – Node Diagram Converted from Figure 3.8

Data Collection

In order to develop a comprehensive dynamic ramp metering control model for the I-80, the required types of data include:

- Geometric data
- Mainline volumes and speeds
- Ramp volumes and speeds
- Origin/Destination (O/D) demand or turning percentage

NJDOT was the principal data provider while some information was obtained from a report by Parsons Brinckerhoff Quade & Douglas Inc., Garmen Associates, and New Jersey Institute of Technology.

The collected geometric data include: (1) freeway link lengths and number of lanes, (2) ramp locations, lengths, and number of lanes, (3) lengths and number of auxiliary lanes, (4) locations where geometry changes, (5) grades, and (6) radius of the curvature. All geometric data, summarized in Table 3.1, were collected from construction plans, provided by NJDOT. All traffic data of eastbound I-80 collected during weekdays in peak period 6:00 AM - 9:00 AM are shown in Table 3.2, while Origin/Destination (O/D) demand distribution are summarized in Table 3.3. These data will be applied for developing a simulation model to evaluate benefits of ramp metering control for the study site. From Table 3.2, we found that the average speeds on the segments from mileposts (MPs) 34.6 to 39.6 were very low. One of main reasons led to the congestion during peak hour would be the higher merging volumes from on-ramps (e.g., MP 34.6 and MP 37.9).

Table 3.1 Geometric Data

				AUXILIARY LANE								
				ONE		TWO		THREE				
LINK NAME	**TYPE**	**LNGTH (FT)**	**NO.THRU LANES**	**TYPE**	**LNGTH (FT)**	**TYPE**	**LNGTH (FT)**	**TYPE**	**LNGTH (FT)**	**THRU DEST NODE**	**CURV RADIUS (FT)**	**GRADE (%)**
(8300,300)	F	0	3	-	-	-	-	-	-	301	0	0
(300,301)	F	5808	3	D	400	-	-	-	-	302	5000	1
(301,302)	F	1320	3			-	-	-	-	303	0	0
(302,303)	F	1056	3	A	400	-	-	-	-	340	0	0
(303,340)	F	14942	3	A	400	D	400	-	-	341	7500	0
(340,341)	F	5370	3	-	-	-	-	-	-	351	7500	0
(341,351)	F	2930	3	A	1000	A	800	D	400	352	0	0
(351,352)	F	1470	4	-	-	-	-	-	-	371	0	2
(352,371)	F	10200	4	A	650	D	650	-	-	372	0	1
(371,372)	F	1050	4	-	-	-	-	-	-	373	2000	-2
(372,373)	F	1100	4	A	640	-	-	-	-	381	2000	0
(373,381)	F	5770	4	A	650	D	650	-	-	391	6000	0
(381,391)	F	4326	4	-	-	-	-	-	-	411	3500	0
(391,411)	F	6280	4	A	935	-	-	-	-	8411	5000	-2
(301,305)	R	845	1	-	-	-	-	-	-	8305	500	0
(8306,206)	R	0	1	-	-	-	-	-	-	306	600	0
(206,306)	R	729	1	-	-	-	-	-	-	302	600	0
(306,302)	R	400	1	-	-	-	-	-	-	303	600	0
(8307,207)	R	0	1	-	-	-	-	-	-	307	0	0
(207,307)	R	387	1	-	-	-	-	-	-	303	2500	0
(307,303)	R	400	1	-	-	-	-	-	-	340	2500	0
(340,346)	R	1192	1	-	-	-	-	-	-	8346	500	0
(8345,245)	R	0	2	-	-	-	-	-	-	345	1100	0
(245,345)	R	1250	2	-	-	-	-	-	-	341	1100	0
(345,341)	R	400	2	-	-	-	-	-	-	351	1100	0
(351,355)	R	600	1	-	-	-	-	-	-	8355	1100	0
(8356,256)	R	0	1	-	-	-	-	-	-	356	0	0
(256,356)	R	300	1	-	-	-	-	-	-	352	0	0
(356,352)	R	400	1	-	-	-	-	-	-	371	0	0
(371,375)	R	829	1	-	-	-	-	-	-	8375	0	0

Note: A: acceleration lane, D: deceleration land, F: freeway, R: ramp

Table 3.2 Traffic Data

Location (Mile Post)	Intersect with	Lane #	Length (ft.)	Signalized	Storage Area (# Cars)	Speed Limit (mph)	Volume* (peak) (vph)	Avg. Speed* (mph)	Capacity* (vph)
MP (29.2-30.3)	-	3	-	-	-	65	3370	56	5700
MP (29.2) On-Ramp	Landing Road	1	438	No	22	-	-	-	-
MP (30.3-30.6)	-	3	-	-	-	65	3490	55	5700
MP (30.3) Off-Ramp	Howard Blvd.	1	845	No	42	25	260	-	-
MP (30.6-30.75)	-	3	-	-	-	65	3490	55	5700
MP(30.6) On-Ramp	Howard Blvd.	1	1129	No	56	-	360	-	-
MP (30.75-33.58)	-	3	-	-	-	65	3490	55	5700
MP (30.75) On-Ramp	Howard Blvd.	1	787	No	39	-	360	-	-
MP (33.58-34.6)	-	3	-	-	-	65	3490	55	5700
MP (33.58) Off-Ramp	Main St.	1	1192	No	60	-	780	-	-
MP (34.6-35.2)	-	4	-	-	-	65	4550	6	4440
MP (34.6) On-Ramp	Route 15	2	1650	No **	83	-	2159	-	-
MP (35.2-35.6)	-	4	-	-	-	65	4660	24	4680
Off-Ramp B (35.2)	Mt. Hope Ave.	1	600	Yes	30	30	320	-	-
MP (35.6-37.3)	-	4	-	-	-	65	4660	24	4680
MP(35.6) On-Ramp	Mt. Hope Ave.	1	700	Yes	35	-	819	-	-
MP (37.3-37.6)	-	4	-	-	-	65	5840	19	5760
MP (37.3)Off-Ramp	Hibernia Ave.	1	829	Yes	41	20	410	-	-
MP (37.6-37.9)	-	4	-	-	-	65	5840	19	5760
MP (37.6)On-Ramp	Hibernia Ave.	1	805	No	40	20	400	-	-
MP (37.9-38.9)	-	4	-	-	-	65	5840	19	5760
MP(37.9) On-Ramp	Hibernia Ave.	1	870	No	44	-	1216	-	-
MP (38.9-39.6)	-	4	-	-	-	65	5840	19	5760
MP(38.9) Off-Ramp	Route 46	1	653	No	33	20	710	-	-
MP (39.6-42.3)	-	4	-	-	-	65	5510	24	5580
MP(39.6) On-Ramp	E. Main St.	1	495	No	25	25	430	-	-

*: "Final Report: I-80 Corridor Transportation Needs Assessment" by Garmen Associates.[17]

* *: Intersection with stop sign control.

The storage area is defined as the length of the ramp divided by the average vehicle length (20ft).

Table 3.3 O/D Demand Distribution (%)

O\D	300	301	302	303	340	341	351	352	371	372	373	381	391	411	Sum
300	-	6	-	-	11	-	3	-	5	-	-	6	-	69	100%
301	-	-	-	-	-	-		-	-	-	-	-	-	-	-
302	-	-	-	-	13	-	2	-	5	-	-	6	-	74	100%
303	-	-	-	-	14	-	2	-	5	-	-	6	-	73	100%
340	-	-	-	-	-	-		-	-	-	-		-	-	-
341	-	-	-	-	-	-	8	-	6	-	-	7	-	79	100%
351	-	-	-	-	-	-	-	-	-	-	-		-	-	-
352	-	-	-	-	-	-	-	-	8	-	-	8	-	84	100%
371	-	-	-	-	-	-	-	-	-	-	-		-	-	-
372	-	-	-	-	-	-	-	-	-	-	-	12	-	88	100%
372	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
381	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
391	-	-	-	-	-	-	-	-	-	-	-	-	-	100	100%
411	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

SIMULATION NETWORK MODELING

Computer simulation is one of the most important tools in evaluating traffic operations. It is possible to predict the effect of traffic control and the performance of Transportation Systems Management (TSM) strategies if a transportation network can be simulated on a computer by means of a simulation model. The prediction of the effect could be expressed in terms of measures of effectiveness (MOEs), which include average speeds, number of vehicle stops, delays, vehicle-hours of travel, vehicle-miles of travel, fuel consumption, and pollutant emissions. While the MOEs provide insight into the effect of the applied strategy on the traffic stream, they also provide the basis for optimizing that strategy.

Introduction

There is a great deal of skepticism as to whether ramp metering control can be successfully implemented in New Jersey. Several previous studies (See references 3, 12, 13, 28, 34, and 35) focused on the success of metering control systems in various cities and how their guidelines and criteria could be modified and potentially applied locally, especially for the areas with short ramps. The goal of this study is to assess the potential effects of implementing ramp metering control into a segment of eastbound I-80, New Jersey. To achieve the objective, a state-of-the-art simulation model CORSIM was selected for evaluating metering control strategies by quantifying metering impacts on freeway traffic operations. A simulation approach, rather than an actual field testing approach, was chosen for the following reasons.

- Computer simulation is less costly. Some MOEs (e.g., throughput and delay), while cannot be measured in the field due to time and cost constraints, can be easily approximated with simulation. It is relatively inexpensive to obtain data from simulation outputs.
- With computer simulation, the disruption of traffic operations caused by field experiments will be completely avoided. For different traffic schemes, experimentation with various combinations of diverted traffic volumes, ramp metering rates, and origin and destination demand distributions are impractical in field study, especially for incident-based congestion.

- When significant physical changes to the facility are required in many schemes, which are not acceptable for experimental purposes, computer simulation could be easily used.
- Evaluation of the operational impact of future traffic demand has to be conducted by using simulation or an equivalent analytical tool. In addition, many variables can be held constant, and results could be quickly obtained.
- The availability of traffic simulation models greatly expands the opportunity for the development of new and innovative TSM concepts and designs. Planners and engineers are no longer restricted by the lack of a mechanism for testing ideas prior to field demonstration. Furthermore, because simulation models produce information that allows designers to identify the weakness in concepts and designs, they provide the basis to identify the optimal form of candidate approaches. Thus, the eventual field implementation will have a high probability of success.

Simulation Tool – TSIS, TRAFVU and CORSIM

The Windows version of TSIS 5.0 provides an integrated, user-friendly interface and environment for executing the CORSIM traffic simulation model. Specifically, it is designed to support the CORSIM simulator and CORSIM output processor, TRAFVU™. The user can extend TSIS functionality by adding other traffic engineering or analysis tools that have been designed to conform to the TSIS traffic tool interface. The advantages of operating within the TSIS environment include an intuitive and user-friendly graphical interface; scrollable screen output; better memory management for CORSIM; and on-line context-sensitive help that encompasses the TSIS, TRAFVU, and CORSIM User's Guides.

TRAFVU (TRAF Visualization Utility), the graphics processor deployed by FHWA's Traffic Research Laboratory (TREL), is a state-of-the-art, object-oriented, user-friendly graphics post-processor for CORSIM. TRAFVU displays traffic networks and animates simulated traffic, signals, and MOEs.

CORSIM, a microscopic corridor traffic simulator developed by Federal Highway Administration (FHWA), has been applied extensively to wide variety of areas by both practitioners and researchers and is one of the most wildly used traffic simulation models. It can simulate stochastic individual vehicle movement and control systems on integrated networks containing freeway and surface streets. The behavior of each vehicle is represented in the model through interaction with its surrounding environment including roadway geometry and adjacent vehicles. CORSIM can simulate fairly complex geometric conditions (e.g., curvature, super-elevation, lane add/drop, acceleration / deceleration lanes, grade section, and interchanges) and realistic driver behavior after the model is appropriately calibrated and validated. CORSIM is capable of simulating most freeway geometric, traffic, and surveillance and control conditions by different card types. Thus, CORSIM was selected for testing and evaluating the developed ramp metering control model in this project.

In general, control, geometric and traffic information (as shown in Table 4.1) are main data required by CORSIM. Control data include information of number of time periods, the duration of each time period, the time interval duration, and desired output, etc. Geometric data include number of lanes, length of links, grades of links and curve radius of links, etc. Traffic data include information of traffic volumes and composition, speed, and O/D demand, etc.

Table 4.1 Required Data for CORSIM

Item	Control Data	Geometric Data	Traffic Data
1	number of time periods	number of lanes	volume
2	duration of each time period	lengths of links	speed
3	time interval duration	grades of links	O/D
4	desired output	curve radius of links	vehicle type

Network Modeling

The network of the study site begins from MP 29.2 and ends at MP 41.1 of eastbound I-80, which contains seven on-ramps and five off-ramps. The geometric configuration and link-node diagram were generated and shown in Figures 3.8 and 3.9, respectively.

The first step of network modeling with CORSIM is to determine the relationship among links and nodes. A link connects two nodes, which represents a directional freeway or ramp segment. For entry and exit links, a dummy node is placed between the entry or exit node and the internal node, which allows for the collection of traffic statistics of the links.

The network was coded along the mainline considering critical points such as interchanges, potential ramp meter locations, curvature/superelevation change, and entry or exit points. In the developed simulation model, it contains 8 entry nodes, 6 exit nodes, 14 dummy nodes and 19 internal nodes, while 8 entry links, 6 exit links and 32 internal links connect the total 47 nodes. The detail link/node identification numbers of the study network are summarized in Table 4.2.

Table 4.2 Links and Nodes of the Simulation Network

Link						Node						
Entry	Internal				Exit	Entry	Dummy		Internal			Exit
(8300,300)	(300,301)	(371,372)	(207,307)	(371,375)	(305,8305)	8300	300	375	301	372	376	8305
(8306,206)	(301,302)	(372,373)	(307,303)	(372,376)	(346,8346)	8306	305	276	302	373	377	8346
(8307,207)	(302,303)	(373,381)	(340,346)	(376,276)	(355,8355)	8307	206	277	303	381	395	8355
(8345,245)	(303,340)	(381,391)	(245,345)	(277,377)	(375,8375)	8345	207	385	340	391	-	8375
(8356,256)	(340,341)	(391,411)	(345,341)	(381,385)	(276,8376)	8356	346	295	341	306	-	8411
(8376,276)	(341,351)	(301,305)	(351,355)	(372,376)	(411,8411)	8376	245	411	351	307	-	-
(8377,277)	(351,352)	(206,306)	(256,356)	(295,395)	-	8377	355	-	352	345	-	-
(8395,295)	(352,371)	(306,302)	(356,352)	(395,391)	-	8395	256	-	371	356	-	-

Calibration and Validation

To conduct a feasibility study for evaluating various ramp metering control strategies considering time varying demand, simulation as mentioned before, is a viable approach. To conduct a credible simulation analysis, one must be confident that simulation results should represent real world traffic operations reasonably well. Therefore, the procedure for calibrating and validating of the simulation model should be carefully performed.

Before implementing a ramp metering control plan at the study site, it is essential to demonstrate that traffic engineers have done the best design for the plan. To achieve this goal, the calibrated and validated simulation model used for emulating traffic conditions on I-80, plays an important role to evaluate candidate ramp metering control plans and assess the corresponding impact on the study site.

The impact incurred by implementing different ramp metering control plans can be assessed by simulated MOEs including volume, total delay, and average speed. Then, the best plan that achieves the optimal objective can be identified.

In order to calibrate the simulation model, the MOEs generated by CORSIM must be compared with field data to ensure that simulation results can represent realistic traffic operations of the study site.

Data Collection and Processing

Two data sets collected from the study site during different time periods were used for calibrating and validating the simulation model. The traffic volume and average speed used for calibrating the developed simulation model were collected. Table 4.3, for example, shows the volume and speed data collected during 7:00 am -8:00 am on link 302-303. The traffic volume data used for validating the simulation model were collected during 8:00 am-9:00 am from the same data stations. The average volume and speed on this link was 4260 vph and 47.9 mph, respectively. However, only traffic volumes were provided by data stations at MP 35.1, MP 35.2, and MP 38.1, as shown in Table 4.4.

Table 4.3 Volume & Speed Data (Link 302-303, MP 30.2, 7:00 am-8:00 am)

Date	Right Lane		Middle Lane		Left Lane	
	Volume (vphpl)	**Speed** (mph)	**Volume** (vphpl)	**Speed** (mph)	**Volume** (vphpl)	**Speed** (mph)
10/11/99	1117	60.5	1691	63.2	1779	64.5
10/12/99	1001	37.3	1325	44	1292	44.2
10/13/99	1310	42.2	1589	45.8	1684	46.4
10/14/99	1195	39.7	1475	43.4	1580	43.5
Average	1156	45	1520	49.1	1584	49.7

Table 4.4 Volume Data (8:00 am-9:00 am, May 26, 1999)

	Data Station at		
	MP 35.1	**MP 35.2**	**MP 38.1**
Volume (vphpl)	1598	1755	1560

Model Calibration

The data describing freeway geometry, traffic conditions (volumes, speeds and turning movement) and facility locations (e.g., locations of ramps and warning signs) were the major input of CORSIM. Traffic operations during a peak hour (7:00am-8:00am) on the eastbound of I-80 were simulated. After comparing simulation results with field data, discrepancies were found and reduced by calibrating parameters in CORSIM. The parameters, such as car-following sensitivity factor (defined by time headway between vehicles), lane change parameter, minimum separation for vehicle generation, collision avoidance time period and percentage of cooperative driver, were adjusted to fine tune simulated driving behavior.

There is no certain way to clarify the impact when changing several parameters at a time, due to the interdependent influence among those parameters and the simulation results. Therefore, the impact of each parameter to simulation results was investigated. In order to identify the key parameters influencing the simulation results, the sensitivity analysis for various parameters was conducted. The calibrated values of parameters are shown in Tables 4.5 and 4.6.

Table 4.5 Car-Following Sensitivity Factor

Driver Type	1	2	3	4	5	6	7	8	9	10
Default Value (hundredth of a second)	150	140	130	120	110	100	90	80	70	60
Calibrated Value (hundredth of a second)	130	120	110	100	90	80	70	60	50	40

Table 4.6 Other Calibrated Parameters

Parameter	Default Value	Calibrated Value
Minimum separation for generation of vehicles (tenth of a second)	18	12
Parameter for collision avoidance time period (%)	1	2
Percentage of Corporate Drivers (%)	20	60

Figures 4.1, 4.2 and 4.3 shown below demonstrate the sensitivity of calibrated parameter to the simulation results. From these figures, it is concluded that different values of parameters could generate different levels of influence to the network traffic operations. For example, decreasing the values of car-following sensitivity factor could achieve larger traffic volumes and higher speeds due to shorter gaps allowable between vehicles. With more cooperative drivers, traffic volumes on ramps and their speeds might increase because more vehicles were able to merge into the traffic stream on the mainline.

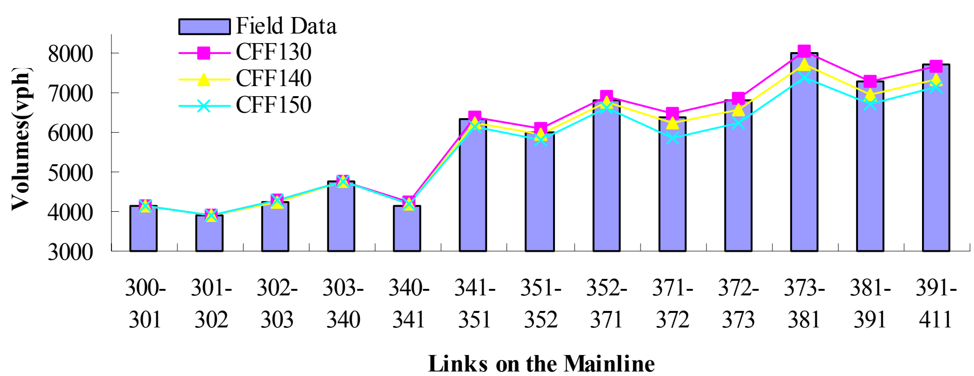

Figure 4.1 - Traffic Volumes on Different Links for Various Car Following Sensitivity Factors (CFF)

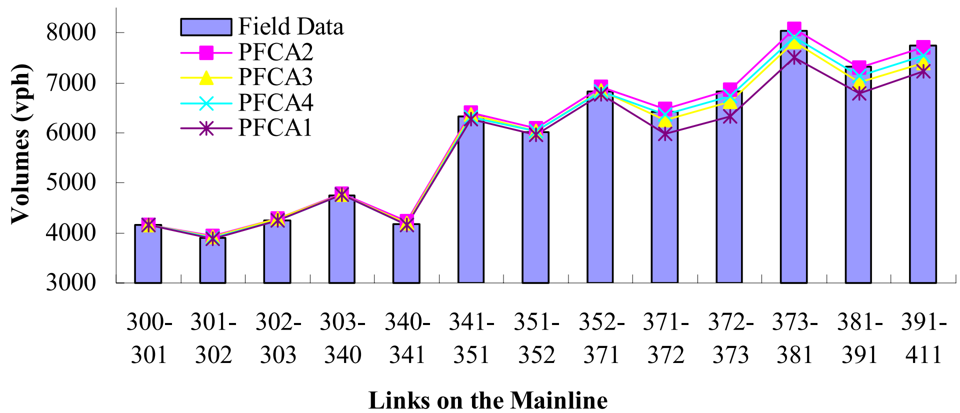

Figure 4.2 - Traffic Volumes on Different Links for Various Parameters for Collision Avoidance (PFCA) Time Periods

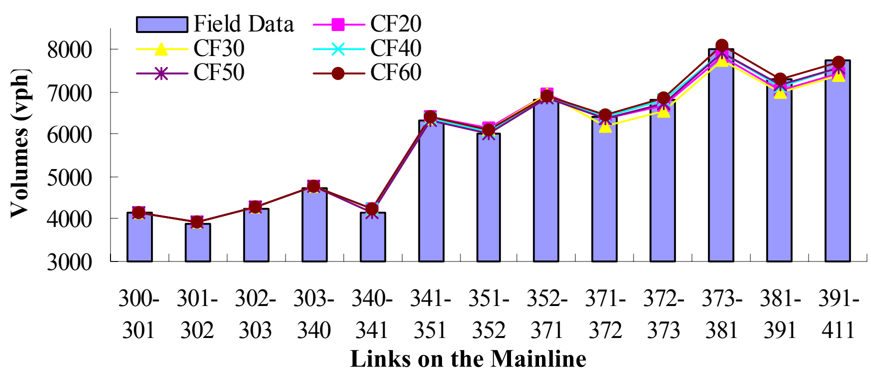

Figure 4.3 - Traffic Volumes on Different Links for Various Courtesy Factors (CF)

Matrix of Origin/Destination (O/D) Percentage

For describing the turning movement of vehicles in the network, card type 25 in CORSIM gives turning percentages for every link with an off-ramp. However, the O/D percentage of vehicles generated based on card type 25 has significant deviation with the actual O/D percentage of the network. Thus, card type 74 (O/D) was used to adjust the turning movements to each off-ramp. The adjusted O/D percentage information is shown in Table 4.7.

Table 4.7 Matrix of Origin and Destination Demand Percentages

O \ D	301	340	351	371	381	411	Total
300	6	11	3	5	6	69	100
302	0	13	2	5	6	74	100
303	0	14	2	5	6	73	100
341	0	0	8	6	7	79	100
352	0	0	0	8	8	84	100
372	0	0	0	0	12	88	100
373	0	0	0	0	12	88	100
391	0	0	0	0	0	100	100

Results Comparison

The calibration procedure adopted in this study is composed by the following comparisons: graphical comparison, aggregate comparison, and statistical comparison.

1. Graphical Comparison

The graphical comparison is a subjective validation approach, which is especially useful for testing the results generated by the simulation model preliminarily. It makes the comparison easy and visible.

2. Aggregate Comparison

Aggregated means and standard deviations give general indication of system performances in real world and in simulation. However, they do not present accurate trend or indication how variables perform over time, what patterns are created, or how much individual measurements deviate. Aggregate comparison along with the graphical comparisons of scattered plots, reveals the similarities and discrepancies of the magnitude and changing pattern for variables.

3. Statistical Comparison

The statistic analysis is crucial for validating the proposed model based on sample data collected from the study site and simulation. It can be used for accessing the accuracy of the model, testing various hypotheses and determining degree of correlation between field data and simulation results. The following indices are used for statistical comparison.

- Mean Absolute Percent Error (MAPE)

MAPE measures the percentage error between simulation results and field data, which can be estimated by Eq. 3:

$$\text{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\frac{|S_i - O_i|}{O_i}*(100\%) \tag{3}$$

where *n*, S_i and O_i are sample size, observation *i* of simulation output, and observation *i* of field measurement, respectively.

- Root Mean Square Error (RMSE)

RMSE denotes the error between simulation results and field data, which can be estimated by Eq. 4:

$$\text{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_I)^2} \tag{4}$$

where *n*, S_i and O_i have been defined in Eq. 3.

Figures 4.4 and 4.5 show that both the simulated and the field observed traffic volumes at various sections on the mainline and ramps were quite close. Note that the field traffic volume on each link was derived based on two data stations on the mainline (approximately at MP 30.2 and MP 35.2) because the volumes reported from other data stations were inconsistent to the field data and not used for calibration.

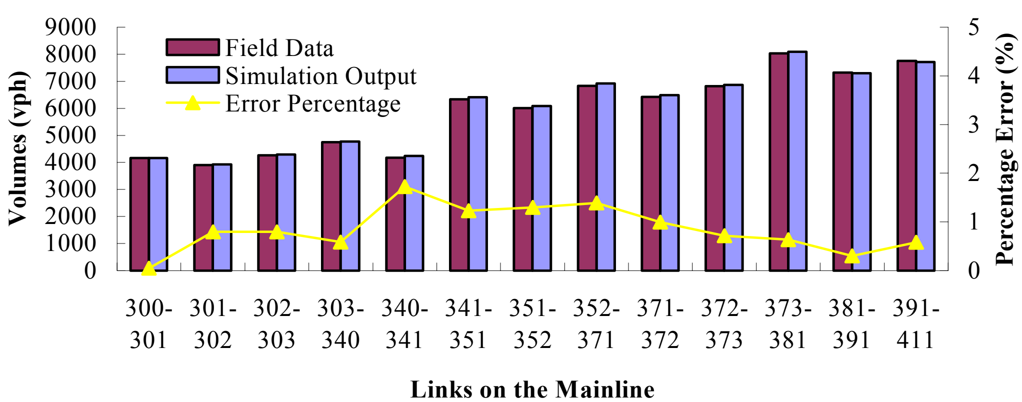

Figure 4.4 - Field Data vs. Simulation Results (Mainline)

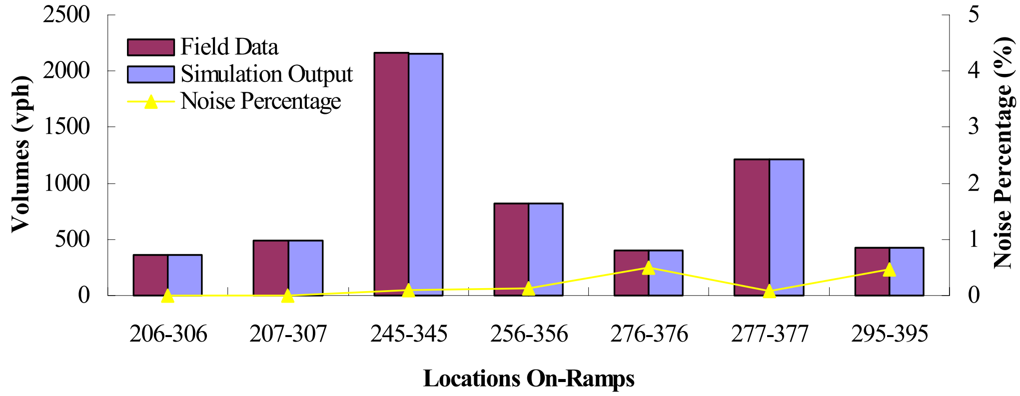

Figure 4.5 - Field Data vs. Simulation Results (On-Ramps)

Model Validation

On a system-wide basis, in order to make sure that the model could produce reliable and accurate estimates of real network traffic condition, model validation is required. The calibrated model was validated through comparing simulation outputs with their field counterparts. It should be noted that the data set used to validate the model were different from that used to calibrate the model. In this study, volumes on the same links collected from different time period were used to validate the model. The preliminary test of traffic volumes was conducted by graphically comparing the values of field observations and simulation results.

The statistical analysis was conducted by calculating MAPE and RMSE for the field and simulated traffic volumes on mainline links. The MAPE and RMSE of traffic volumes were plotted in Figures 4.6 and 4.7, respectively. Figure 4.6 shows that for 364 simulation outputs, the MAPE ranged from 0% to 1.5%. In Figure 4.7, the RMSE of traffic volumes ranged from 0 veh to 35 veh. The simulation model demonstrated its capability to emulate traffic volumes operating on the studied network.

Regarding the speed data, only the station at MP 30.2 provided speed information. Comparing with simulation output, the MAPE was 1.54% and RMSE was 0.97 mph. It demonstrated that the simulation model could accurately simulate vehicle speeds at the survey point.

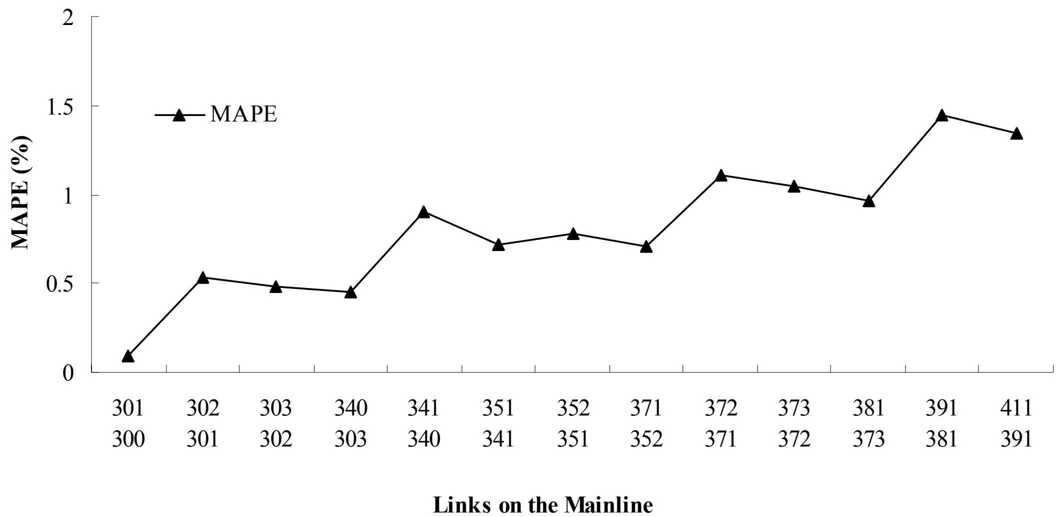

Figure 4.6 - MAPE of Volumes on the Mainline

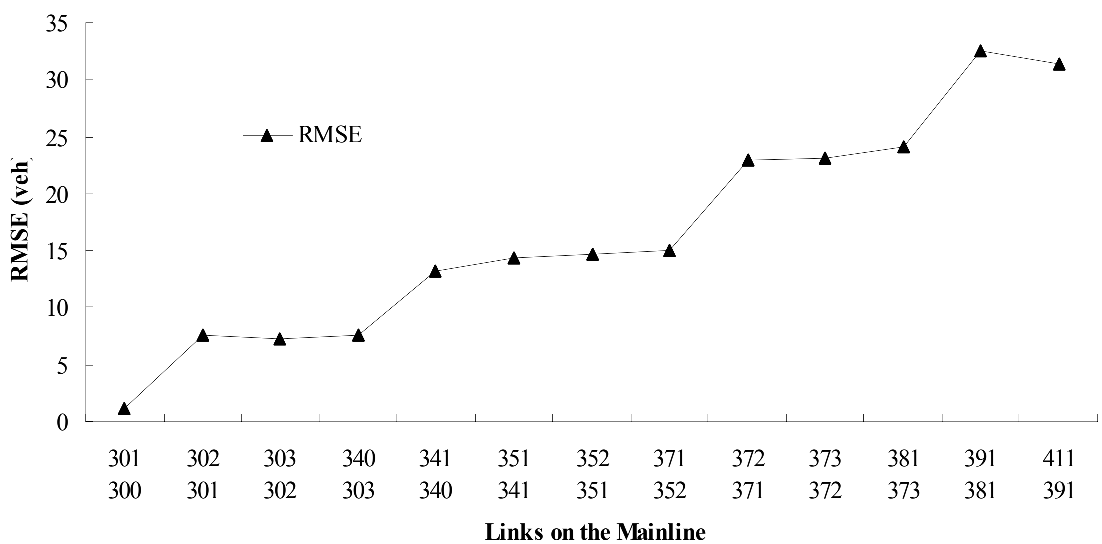

Figure 4.7 - RMSE of Volumes on the Mainline

Summary

In this part, the advantages of computer simulation, the characters and function of simulation tool (e.g., TSIS, TRAFVU and CORSIM) were discussed. The network of the study site from MP 29.2 to MP 41.1 of eastbound I-80 was modeled by CORSIM with colleted control, geometric and traffic data.

The developed simulation model was calibrated and validated based on the field data collected from I-80. By comparing the simulation outputs to the field data, the validity of the simulation model was demonstrated. Both the graphical and aggregate comparison showed that the developed simulation model could adequately simulate traffic operations on eastbound I-80.

Statistical analysis on MAPE and RMSE denoted that the differences between simulation outputs and data collected from the field were very small, which demonstrated that the simulation model was capable of simulating traffic operations in the study site and generating reliable results. Therefore, the calibrated and validated model could be used to simulate the traffic operations and evaluating the benefits of the proposed ramp metering control at the study site.

EVALUATION OF RAMP METERING CONTROL

Ramp metering control refers to the control of vehicles entering freeway mainline from one or more entrance ramps. The purpose of the ramp metering control is to minimize the interference of entering traffic to the mainline traffic and improve freeway traffic operation in a systematic manner. In this part, CORSIM model developed in SIMULATION NETWORK MODELING is applied to evaluate pre-timed and demand/capacity control strategies, since those are most widely applied methods for static and demand responsive metering control.

Constraints

As ramp metering control restricts the number of vehicles merging into the mainline traffic in a given time period, it might generate queues at metered ramps. The paradox is that on one hand the interference to mainline traffic is kept to the minimum and the queue will not be spilled over onto the service roads. Since different ramps have different geometric conditions, it is crucial to ensure that metered ramps have adequate storage capacities. Therefore, before proceeding to simulation analysis, the analysis of ramp meter locations and their corresponding storage capacities should be conducted. Subject to such constraints, feasible metering rates without causing overflow situations at each ramp can be estimated.

Locations of Ramp Meters

To ensure safe merging operation, the location of the ramp meter should be determined by the minimum distance required for a stopped vehicle that can accelerate along the lane and smoothly merge into the mainline traffic stream. Such a minimum distance d is the distance for a stopped vehicle at the ramp meter to the point where the vehicle reaches the speed on the mainline. Based on the Newton's Law, the minimum distance can be obtained from Eq. 5.

$$d = 0.5at^2 + V_0 t \quad (5)$$

where a represents vehicle acceleration rate that can be derived as

$$a = \frac{V_t - V_0}{t} \tag{6}$$

where V_t and V_0 are the average speed on the mainline and the initial speed of a vehicle released by a ramp meter, respectively. For a stop vehicle, V_0 is zero. Since a, V_t, and V_0 are known, the time t required for the vehicle accelerating from the ramp meter to the on-ramp gore can thus be determined. By substituting a, t, and V_0 into Eq. 5, d can be obtained. In this study, the acceleration rates for passenger cars, carpool vehicles, buses, and trucks were assumed to be 6.8, 3.8, 3.5 and 3.2 mph/sec (embedded in CORSIM), respectively. The meter location was determined by the truck acceleration rate (3.2 mph/sec) to satisfy all conditions. The lengths of the auxiliary acceleration lanes of the ramps at the study site are listed in Table 5.1, and the suggested ramp meter locations are summarized in Table 5.2.

Table 5.1 Length of the Accelerated Auxiliary Lane

Link	302-303	303-340	341-351	352-371	372-373	373-381	391-411
Length (feet)	400	400	1000	650	640	650	935

Table 5.2 Distance from Meter Location to the On-ramp Gore

Metered Node	306	307	345	356	376	377	395
Actual Location (feet)	400	400	400	320	330	320	50*

*: The minimum distance from the meter to the on-ramp gore suggested by Ramp Meter Design Guidelines (CADOT, 1991)

An example for determining suggested meter locations is discussed next. Link 372-373 had an auxiliary acceleration lane of 640 ft. In order for a truck to accelerate from stop at the meter to reach the average speed of the mainline traffic (say 65 mph), the required acceleration time t was:

$$t = \frac{V_t - V_0}{a} = \frac{65 - 0}{3.2} = 20.13 \text{ (seconds).}$$

By substituting t into Eq. 6, the minimum distance was

$$d = 0.5at^2 + V_0 t = 0.5 \times 3.2 \times (5280/3600) \times 20.13^2 + 0 \times 20.13 = 951 \text{ (feet)}$$

Apparently, the auxiliary acceleration lane at node 376 was not long enough. Thus, the ramp meter should be located at least 311 feet (951 feet minus 640 feet) before the on-ramp gore. For safety consideration, the ramp meter at node 376 was located 330 feet away from the on-ramp gore. Note that the meter location was also affected by the average mainline speed. If the average mainline speed decreased, the distance between the meter location and on-ramp gore decreased.

Ramp Storage Capacity

In general, ramps provide the necessary linkages between freeways and local streets or arterials. In order to avoid vehicles spillback onto surface streets from a ramp metering control signal, the ramp storage capacity has to be taken into consideration. Since the goal of this project is to optimize ramp metering rates so that the interference to mainline traffic and congestion on local streets can be minimized, the ramp storage capacity serves as an important buffer that can not be ignored when designing a ramp metering control plan.

An example of calculating the minimum metering rate is discussed next. Assume that vehicles approaching an on-ramp follow a Poisson distribution with mean arrival rate λ (in vehicles per hour). If the metering rate is μ (in vehicles per hour), the queue length L_q (number of vehicles) can be estimated by using M/M/1 queuing model as shown in Eq. 7.

$$L_q = \frac{\rho\lambda}{\mu - \lambda} \qquad (7)$$

where ρ is the ratio of vehicle mean arrival rate and the metering rate (λ/μ). In CORSIM, the suggested minimum metering headway is 4 seconds. Thus, the maximum metering rate is 900 vphpl (3600/4 = 900).

Based on the collected data, the entry flows at metering nodes 377 and 345 were 1216 and 1080 vphpl, respectively, while the corresponding vehicle headways were 2.96 and 3.31 seconds per vehicle. Since both headways were less than 4.0 seconds, the queues on both ramps would easily exceed the ramp storage capacity. Thus, metering control was not recommended on both ramps.

The storage capacities for potential metered ramps are shown in Table 5.3. At node 306, for example, the maximum queue length of 729 feet was measured from the entrance of the on-ramp to the meter location. By assuming the average vehicle length of 20 feet, the queue storage capacity was 36 vehicles. Thus, the constraint of this ramp was represented by $L_q \leq 36$. The metering rate μ (370 vph) could be solved by Eq. 7, where the mean arrival rate λ was 360 vph. The resulting headway was 9.7 (e.g., 3600/ 370) seconds per vehicle.

Table 5.3 Storage Capacities of On-ramps

Item	Node					Unit(s)
	306	**307**	**356**	**376**	**395**	
λ	360	489	819	400	430	vph
μ (metering rate)	370	513	860	416	448	vph
ρ	0.973	0.953	0.952	0.962	0.960	-
L_q	35	19	19	24	23	vehicles
Max Queue Length	729	387	380	475	455	feet
Average Vehicle Length	20	20	20	20	20	feet
Queue Storage Capacity	**36**	**19**	**19**	**24**	**23**	**vehicles**
Pre-timed Headway	9.7	7.0	4.2	8.7	8.0	Seconds/vehicle

Simulation Analysis and Evaluation

The evaluation of ramp metering control was conducted by performing extensive simulation with CORSIM. Comparing with no control situation, the benefits of increasing throughput and/or decreasing delay was expected with the implementation of ramp metering control. In order to generate unbiased estimates, ten simulation runs with different random number seeds were performed for each of the three scenarios: no control, pre-timed control, and demand-capacity control situations. The benefit of alternate strategies are evaluated and discussed next.

<u>No Control</u>

Without ramp metering control, vehicles entering the mainline stream from ramps would not be regulated. Under this situation, the network-wide MOEs, such as total throughput and total delay, were obtained based on one-hour simulation. The total throughput was 9613 vph, while the total delay was 17199 vehicle-minutes, which would be used as base results for comparative analysis with various metering control strategies.

Pre-timed Control

Though the simulation of the pre-timed metering control strategy was used on individual on-ramps, the simulated network wide MOEs were analyzed. The applied metering rates were selected subject to the storage constraint of each ramp and the minimum ramp metering rate was derived from Eq. 7. As mentioned earlier, the maximum ramp metering rate in CORSIM was 900 vphpl. Thus, the upper and lower bounds of metering rates for each ramp could be determined. If the metering rate derived from Eq. 7 is not in the feasible range, the metering control on that ramp will not be recommended.

To obtain the optimal pre-timed metering rate, a numerical search method was applied. A series of simulation runs with different metering rates were performed. The boundaries of metering headways and all the simulated metering headways at different ramps are presented in Table 5.4. We found that there were feasible solutions for metering control at nodes 306, 307, 356, 376 and 395. Thus, they were identified as the candidate places to implement ramp metering control.

Table 5.4 Pre-timed Metering Headways

Ramp Meter Site (Node)		306	307	345	356	376	377	395
Pre-timed Headway Range (Seconds/veh)	Min	4.0	4.0	4.0	4.0	4.0	4.0	4.0
		6.0	4.7	-	-	5.0	-	5.0
		8.0	5.5	-	4.1	6.0	-	6.0
		9.0	6.3	-	-	7.0	-	7.0
	Max	9.7	7.0	-	4.2	8.7	-	8.0

All simulation results are summarized in Table 5.5. The highlighted numbers in Table 5.5 represent the best metering rates that the minimum network-wide delay could be achieved. The achieved minimum delays were all less than that under no control situation. The benefits of pre-timed ramp metering control on those ramps were thus quantified.

Ideally, the optimal metering rate was expected to achieve the maximum in throughput and minimum delay at the same time. However, the simulation result did not generate this situation that maybe consistent with the real world traffic operation. Table 5.5 summaries the simulation results for total throughput under pre-time control and no control situations.

Table 5.5 MOEs of Pre-timed Metering Control

Node	Pre-timed Headway (seconds)	Total Throughput (vph)			Total Delay (veh-min)		
		No Control (1)	Pre-timed (2)	[(2)-(1)]/(1) (%)	No Control (3)	Pre-timed (4)	[(4)-(3)]/(3) (%)
306	9.7	9613	9572	-0.43	17199	17429	1.34
	9.0	9613	9638	0.26	17199	16962	-1.38
	8.0	9613	9611	-0.02	**17199**	**16812**	**-2.25**
	6.0	9613	9627	0.15	17199	17010	-1.10
	4.0	9613	9581	-0.33	17199	17789	3.43
307	7.0	9613	9625	0.12	17199	17172	-0.16
	6.3	9613	9617	0.04	**17199**	**16971**	**-1.33**
	5.5	9613	9624	0.11	17199	17037	-0.94
	4.7	9613	9629	0.17	17199	17058	-0.82
	4.0	9613	9584	-0.30	17199	17268	0.40
356	4.2	9613	9507	-1.10	17199	17306	0.62
	4.1	9613	9507	-1.10	**17199**	**16694**	**-2.94**
	4.0	9613	9560	-0.55	17199	18254	6.13
376	8.7	9613	8650	-10.02	17199	17356	0.91
	7.0	9613	9598	-0.16	17199	17089	-0.64
	6.0	9613	9623	0.10	17199	16939	-1.51
	5.0	9613	9602	-0.11	**17199**	**16843**	**-2.07**
	4.0	9613	9605	-0.08	17199	17067	-0.77
395	8.0	9613	9617	0.04	17199	17026	-1.01
	7.0	9613	9585	-0.29	17199	17348	0.87
	6.0	9613	9620	0.07	17199	16968	-1.34
	5.0	9613	9636	0.24	**17199**	**16323**	**-5.09**
	4.0	9613	9587	-0.27	17199	17734	3.11

- At node 306, if the metering rate was 9 sec/vehicle the total throughput increased, while the total delay was reduced. However, if the metering rate was 8 sec/vehicle, the total delay could be reduced; however, the maximum total throughput could not be achieved.

- At node 307, if the metering rate was 4.7 sec/vehicle the total throughput increased, and the total delay was reduced. If the metering rate is 6.3 sec/vehicle, the total delay was reduced, but the maximum total throughput was not achieved.

- At node 356, when pre-time metering control was applied, the total throughput was always less than that under no control situation. When the metering rate was at 4.1 sec/vehicle, the total delay was reduced. Node 356 was not recommended to perform pre-time meter control if the objective was to generate benefit in increasing total throughput.

- At node 376, if the metering was 6.0 sec/vehicle, the total throughput could be increased, while the total delay was also reduced. If the metering rate was 5.0 sec/vehicle, the total delay was reduced, while the total throughput was reduced.

- At node 395, if the metering rate was 5.0 sec/vehicle, the increased total throughput and reduced total delay were achieved at the same time.

From the simulation results, the greatest benefit in reducing delay and increasing throughput usually could not be achieved simultaneously (except at node 395). Future research should be given more attention in analyzing the tradeoff between increased delay and increased throughput. Figures 5.1 through 5.8 show the simulation results for pre-timed metering control at nodes 306, 307, 376, and 359.

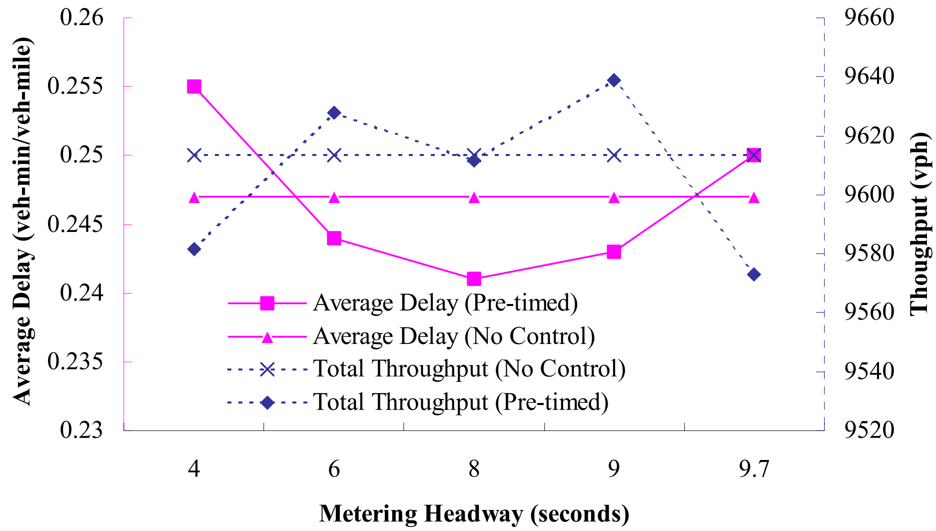

Figure 5.1 - Average Delay and Total Throughput vs. Metering Headway (Pre-timed Metering Control at Node 306)

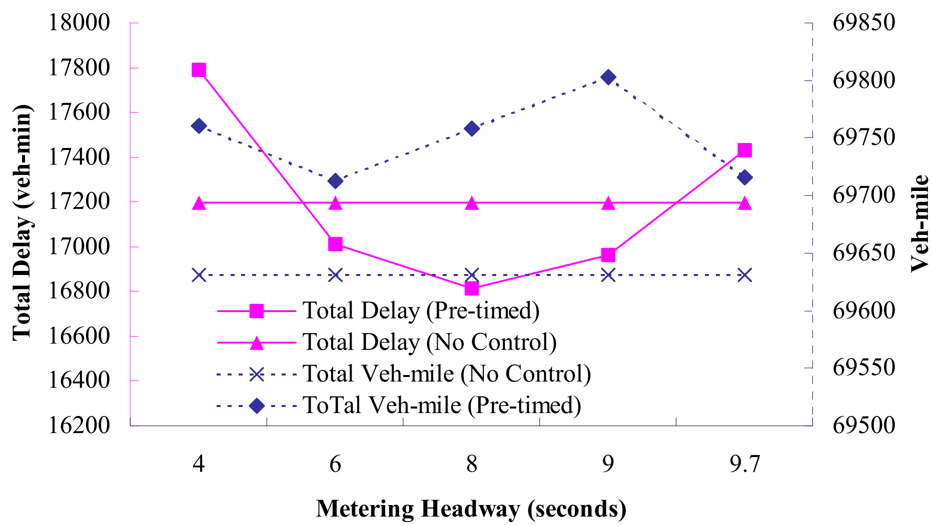

Figure 5.2 - Total Delay and Veh-mile vs. Metering Headway (Pre-timed Metering Control at Node 306)

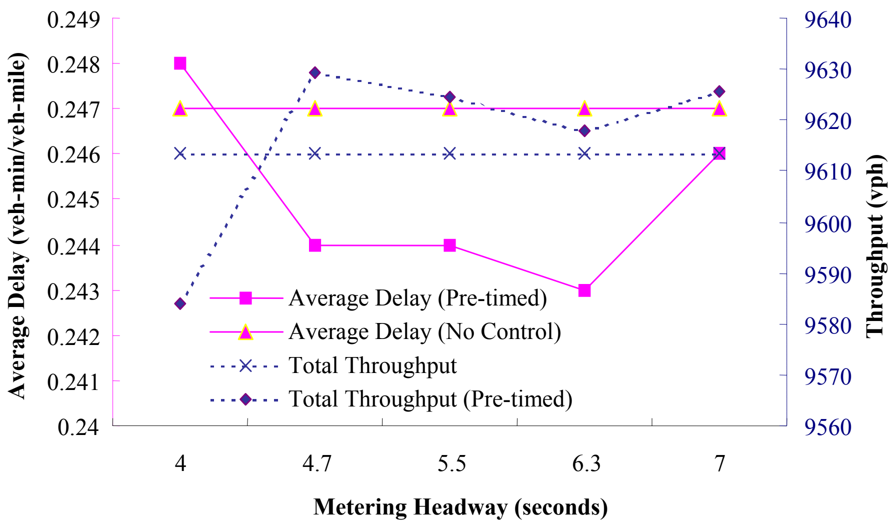

Figure 5.3 - Average Delay and Total Throughput vs. Metering Headway (Pre-timed Metering Control at Node 307)

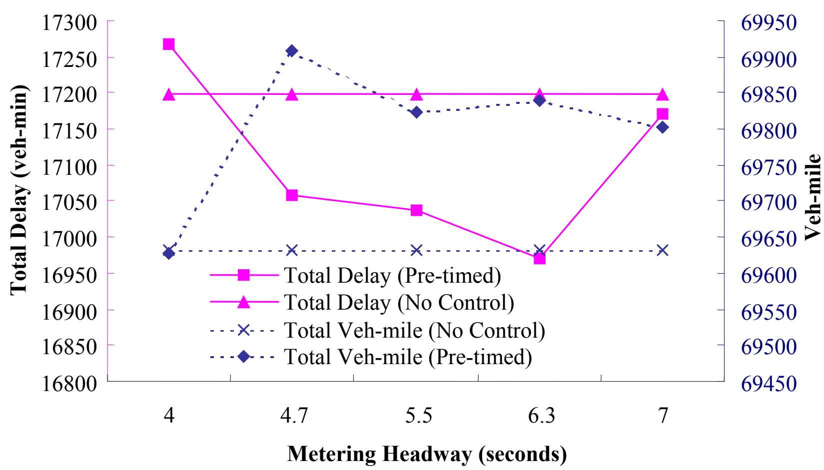

Figure 5.4 - Total Delay and Veh-mile vs. Metering Headway (Pre-timed Metering Control at Node 307)

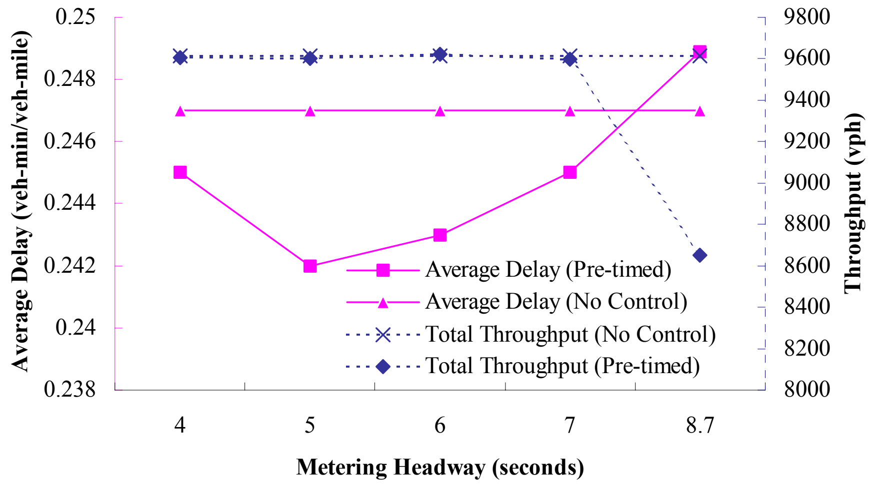

Figure 5.5 - Average Delay and Total Throughput vs. Metering Headway (Pre-timed Metering Control at Node 376)

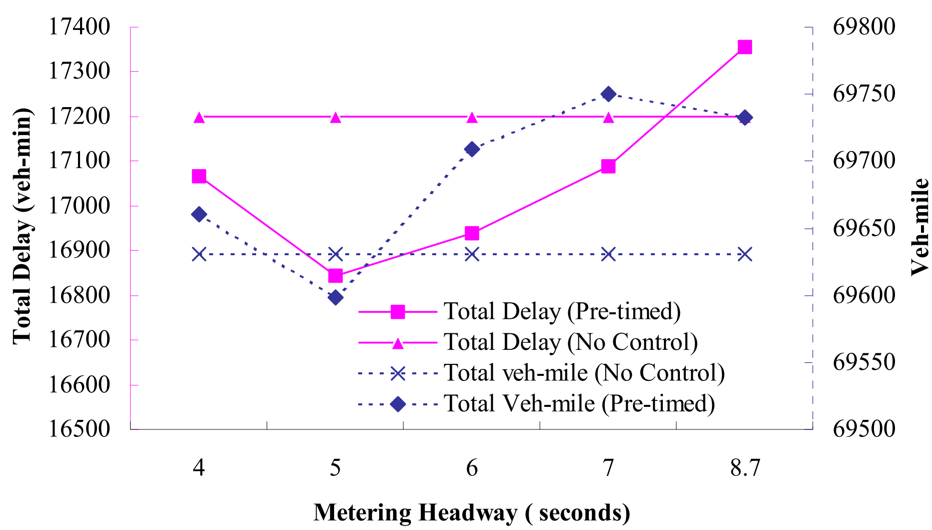

Figure 5.6 - Total Delay and Veh-mile vs. Metering Headway (Pre-timed Metering Control at Node 376)

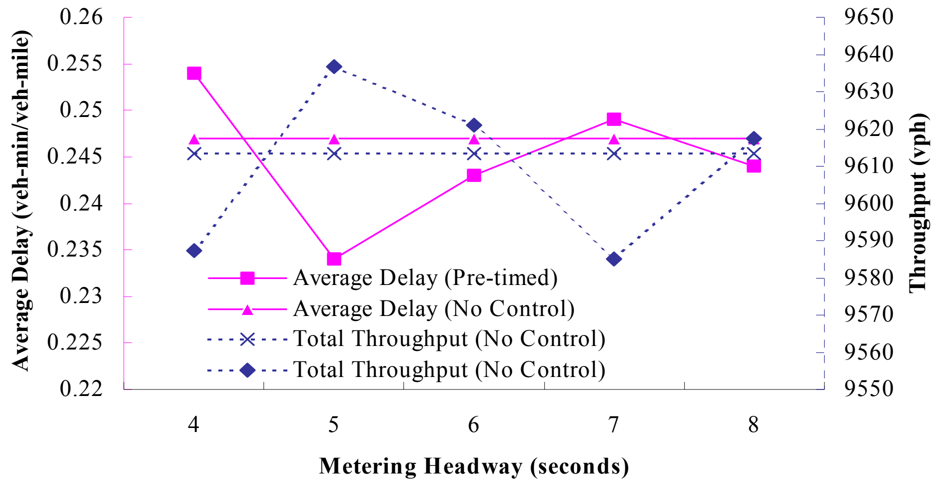

Figure 5.7 - Average Delay and Total Throughput vs. Metering Headway (Pre-timed Metering Control at Node 395)

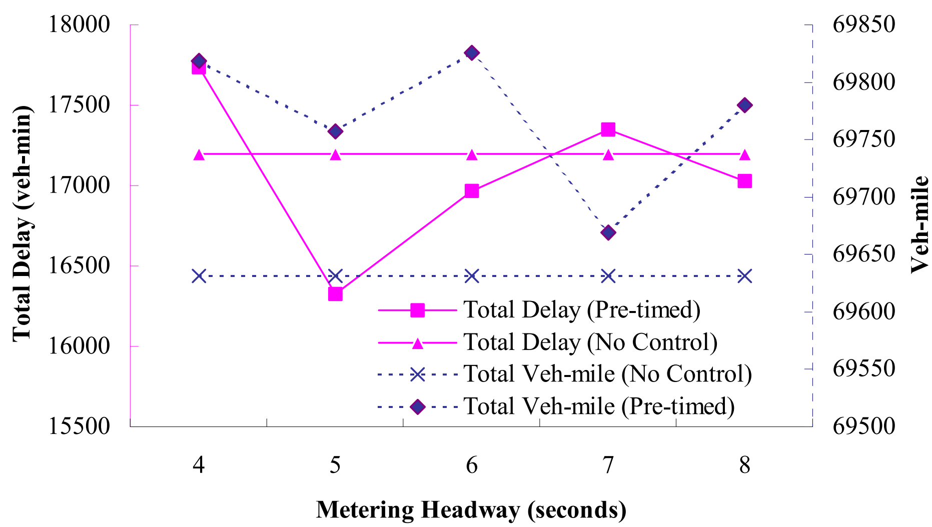

Figure 5.8 - Total Delay and Veh-mile vs. Metering Headway (Pre-timed Metering Control at Node 395)

Demand/Capacity Control

As one of demand responsive control strategies, demand/capacity control can respond to real time traffic conditions to effectively reduce congestion. It requires that the total traffic volume combined from both mainline traffic and those released from the metered on-ramp should not exceed the designated freeway capacity. Therefore, before designing a demand/capacity metering control system, an evaluation of freeway capacity, immediately downstream of the metered on-ramp, should be conducted. By definition, the freeway capacity is the maximum hourly volume at which vehicles can be reasonably expected to traverse a point or uniform segment of a lane during a given time period under prevailing freeway traffic conditions. Traffic counts can be obtained from the surveillance systems (e.g., detectors, CCTV) installed on the freeway. The maximum metering rate is subject to the capacity constraint, while the minimum metering rate considered here is to ensure that queuing vehicles do not spillback onto local streets. Also, the metering rate is always greater than 4 seconds due to the suggestion of CORSIM.

In order to determine the maximum ramp metering rate which will not lead to traffic flow exceeding the capacity on freeway, the mainline capacity should be investigated first. According to the *Highway Capacity Manual* (HCM, 1997), the capacity of the freeway should not be more than 2200 vphpl when the free flow speed is 65 mph. However, if the calibrated values of car-following factor are from 40 to 130 hundreds of a second, the simulated freeway capacity can increase up to 2950 vphpl with CORSIM. In order to analyze optimal metering rates under various freeway capacities, the maximum ramp metering rates were estimated based on freeway capacities ranging between 1800 and 3000 vphpl. The metering headways corresponding to various freeway capacities were calculated based on collected demand data summarized in Table 5.6, where the highlights were the feasible metering rates. Simulation results for implementing metering control at every individual ramp are shown in Table 5.7.

Table 5.6 Metering Headway for Demand/Capacity Control

Capacity on Mainline (vphpl)	Metering Headway (seconds) at nodes				
	306	307	356	376	395
3000	2.12	2.29	2.40	2.51	2.88
2900	2.25	2.44	2.57	2.69	3.12
2800	2.40	2.62	2.77	2.93	3.44
2700	2.57	2.83	3.00	3.16	3.77
2600	2.77	3.06	3.26	3.49	**4.22**
2500	3.00	3.35	3.60	3.84	**4.83**
2400	3.28	3.68	**4.00**	**4.36**	**5.52**
2300	3.60	**4.09**	4.52	**4.92**	**6.52**
2200	**4.01**	**4.63**	5.12	**5.68**	**7.95**
2100	**4.52**	**5.29**	5.93	**6.84**	10.33
2000	**5.15**	**6.26**	7.13	**8.29**	14.50
1900	**6.04**	7.58	8.95	10.90	26.29
1800	**7.24**	9.54	11.94	15.41	80.36
Feasible Headway Range (seconds)	**4.0~9.7**	**4.0~7.0**	**4.0~4.2**	**4.0~8.7**	**4.0~8.0**

Table 5.7 MOEs of Demand/Capacity Control vs. No Control

Metered Node	**Capacity** (veh/hrpl)	**Controlled Headway on Ramp** (seconds/veh)	**On-ramp Metering Rate Range** (seconds/veh)		**Total Throughput** (veh/hour)		**Total Delay** (veh-min)	
			Min	Max	No Control	D/C*	No Control	D/C*
306	2200	4.01	4.0	9.7	**9613**	**9620**	17199	17451
	2100	4.52			9613	9606	**17199**	**17092**
	2000	5.15			9613	9593	17199	17303
	1900	6.04			**9613**	**9620**	17199	17158
	1800	7.24			9613	9610	17199	17170
307	2300	4.09	4.0	7.0	9613	9614	17199	16730
	2200	4.63			9613	9620	17199	17008
	2100	5.29			9613	9626	**17199**	**16587**
	2000	6.26			**9613**	**9636**	17199	16660
376	2400	4.36	4.0	8.7	9613	9611	**17199**	**16461**
	2300	4.92			**9613**	**9631**	17199	17009
	2200	5.68			9613	9596	17199	16844
	2100	6.84			9613	9588	17199	17715
	2000	8.29			9613	9608	17199	16841
395	2600	4.22	4.0	8.0	9613	9583	17199	16878
	2500	4.83			**9613**	**9629**	**17199**	**16647**
	2400	5.52			9613	9599	17199	16807
	2300	6.52			9613	9592	17199	17274
	2200	7.95			9613	9613	17199	17090

D/C: Demand/Capacity Control

As discussed on page 54, metering control would not recommended at nodes 345 and 377 due to possible vehicles spillback onto local streets. The range (4.0 ~ 4.2 seconds) of metering headway at node 356 was not wide enough for implementing demand/capacity control, but pre-timed control might be a suitable alternative.

After applying the demand/capacity control strategy at nodes 306, 307, 376, and 395, the simulated network-wide delay was less than that without metering control, while the total throughput increased. Table 5.8 shows that delay could be significantly reduced under demand/capacity metering control at nodes 307, 376, and 395. However, the corresponding throughputs were increased at nodes 307 and 395. In Table 5.9, it was found that the increased throughputs could be achieved while implementing demand/capacity control at all the four nodes. The corresponding delays were reduced while the demand/capacity control was implemented at nodes 307, 376, and 395, but increased while the demand/capacity control was at node 306. Similar to the pre-timed control, the demand/capacity control could not achieve the maximum total throughput and the minimum total delay simultaneously. Again, the tradeoff between the increased delay and increased capacity should be considered in the future.

Figures 5.8 through 5.16 show the simulation results on average delay and total throughput before and after the demand/capacity metering control at nodes 306, 307, 376, and 395.

Table 5.8 Benefit of Demand/Capacity Control (Reduced Delay)

Metered Node	**Controlled Headway** (seconds/veh)	**Total Throughput** (veh/hour)			**Total Delay** (veh-min)		
		No Control (1)	D/C* (2)	[(1)-(2)]/(1) (%)	No Control (3)	D/C (4)	[(4)-(3)]/(3) (%)
306	4.52	9613	9606	-0.07	17199	**17092**	**-0.62**
307	5.29	9613	9626	0.14	17199	**16587**	**-3.56**
376	4.36	9613	9611	-0.02	17199	**16461**	**-4.29**
395	4.83	9613	9629	0.17	17199	**16647**	**-3.21**

D/C: Demand/Capacity Control

Table 5.9 Benefit of Demand/Capacity Control (Increased Throughput)

Metered Node	Controlled Headway (seconds/veh)	Total Throughput (veh/hour)			Total Delay (veh-min)		
		No Control (1)	D/C* (2)	[(1)-(2)]/(1) (%)	No Control (3)	D/C (4)	[(4)-(3)]/(3) (%)
306	4.01	9613	**9620**	**0.07**	17199	17451	1.47
307	6.26	9613	**9636**	**0.24**	17199	16660	-3.13
376	4.92	9613	**9631**	**0.19**	17199	17009	-1.10
395	4.83	9613	**9629**	**0.17**	17199	16647	-3.21

D/C: Demand/Capacity Control

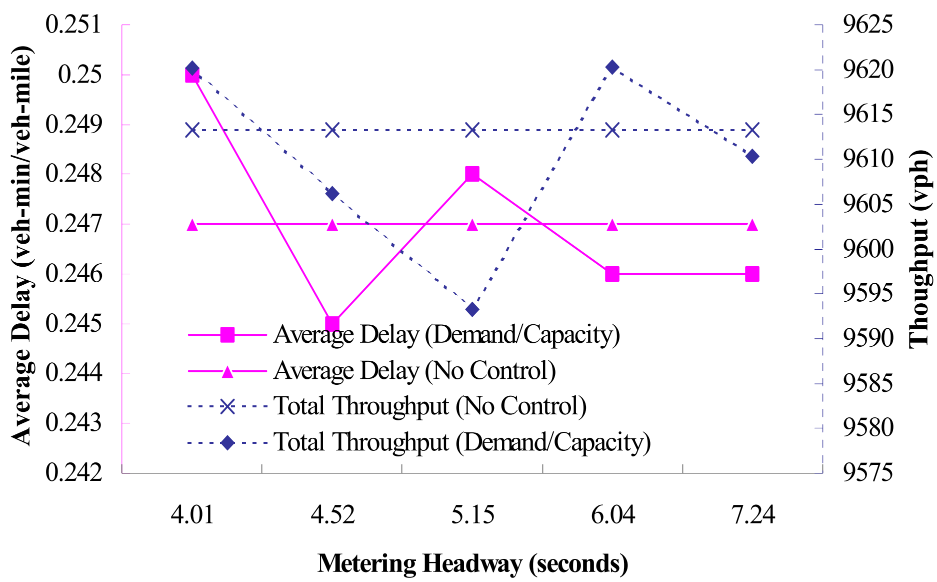

Figure 5.9 - Average Delay and Total Throughput vs. Metering Headway (Demand/Capacity Control at Node 306)

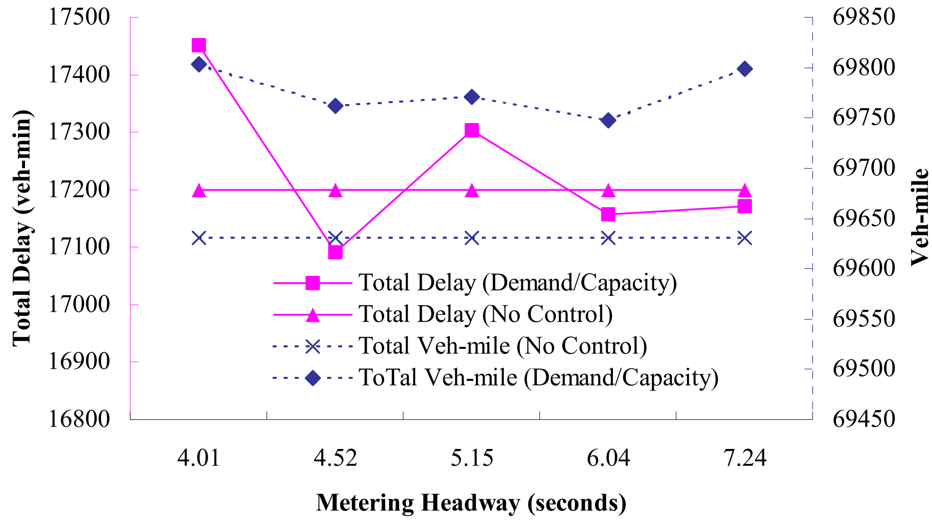

Figure 5.10 - Total Delay and Veh-mile vs. Metering Headway (Demand/Capacity Control at Node 306)

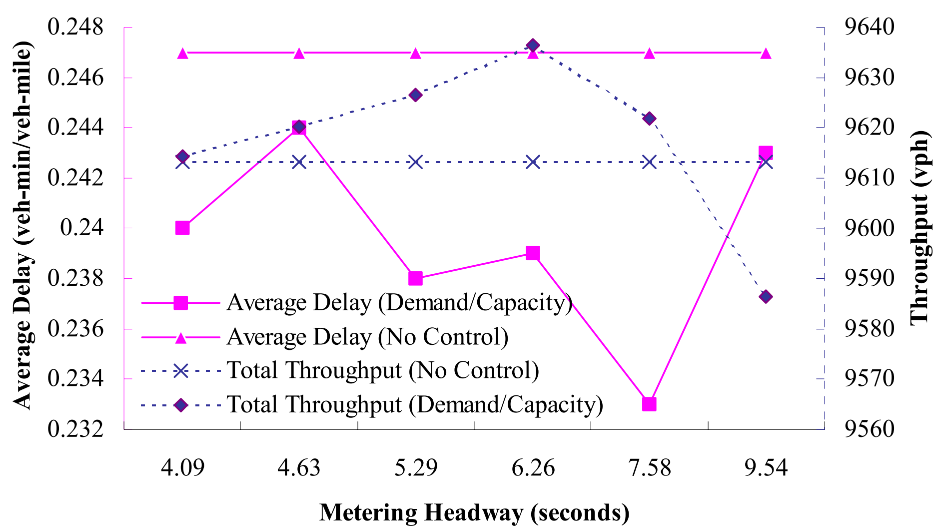

Figure 5.11 - Average Delay and Total Throughput vs. Metering Headway (Demand/Capacity Control at Node 307)

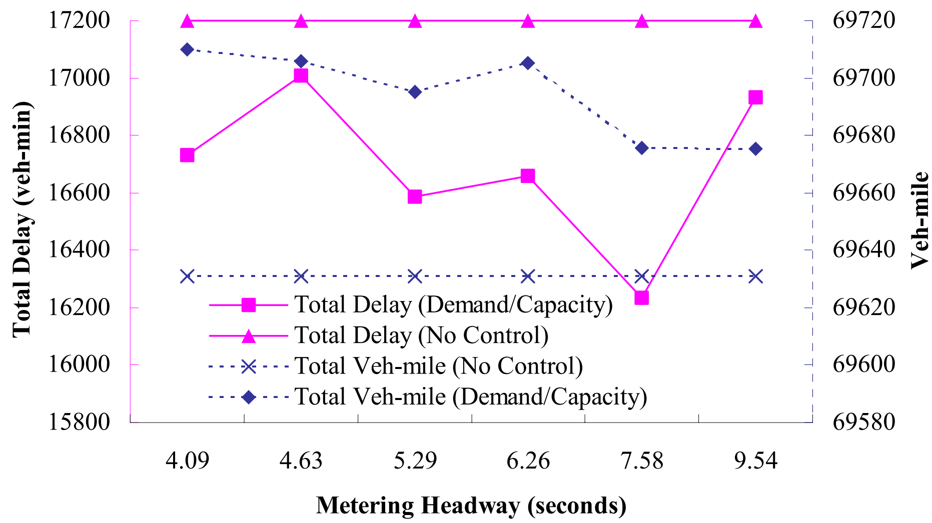

Figure 5.12 - Total Delay and Veh-mile vs. Metering Headway (Demand/Capacity Control at Node 307)

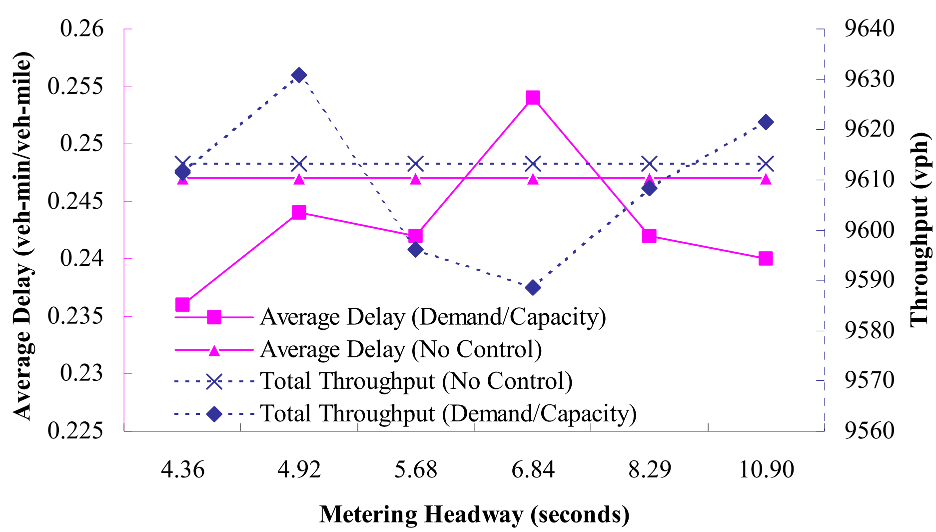

Figure 5.13 - Average Delay and Total Throughput vs. Metering Headway (Demand/Capacity Control at Node 376)

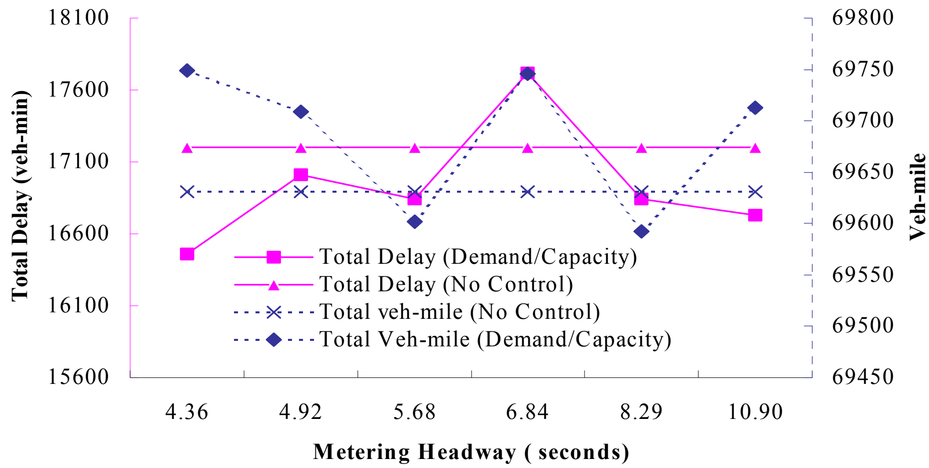

Figure 5.14 - Total Delay and Veh-mile vs. Metering Headway (Demand/Capacity Control at Node 376)

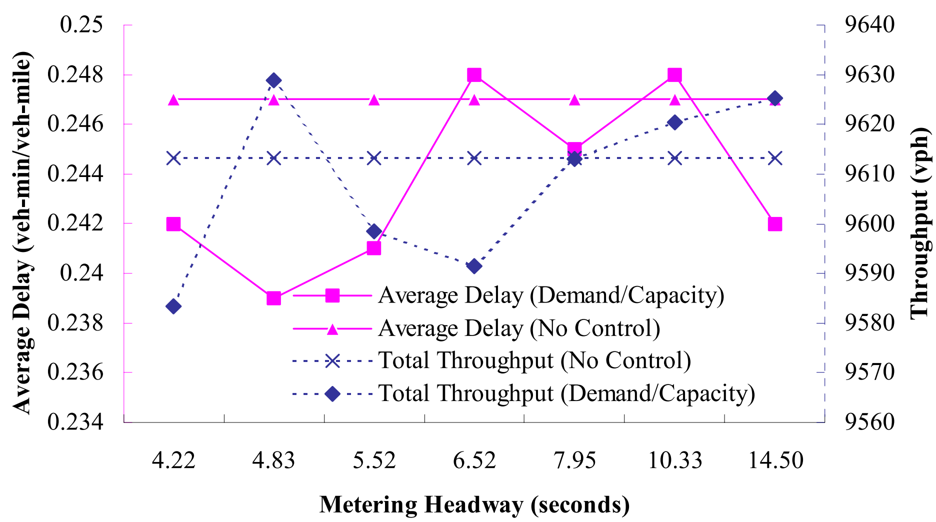

Figure 5.15 - Average Delay and Total Throughput vs. Metering Headway (Demand/Capacity Control at Node 395)

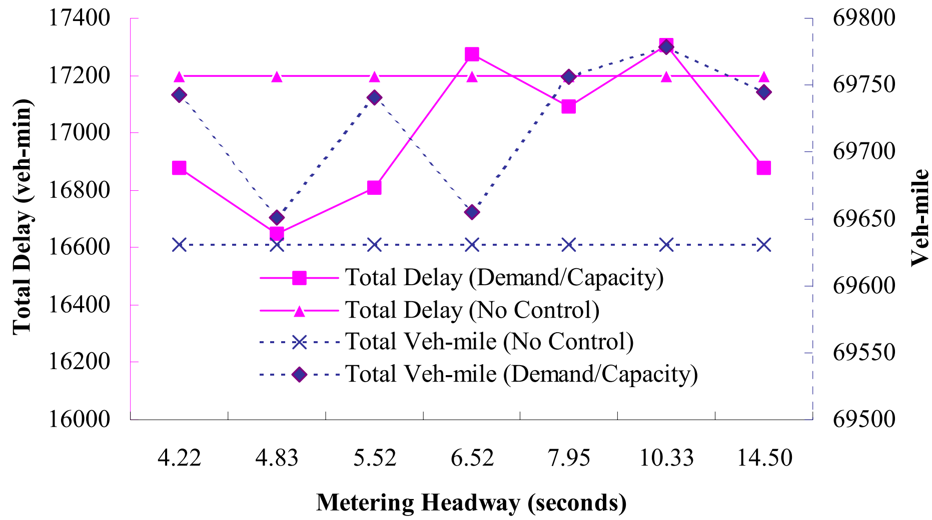

Figure 5.16 - Total Delay and Veh-mile vs. Metering Headway (Demand/Capacity Control at Node 395)

Summary

In this part of the study, the ramp meter location and the ramp storage capacity were calculated through Eqs.5 and 7, respectively. The CORSIM model developed in SIMULATION NETWORK MODELING was applied for testing and evaluating pre-timed and demand/capacity metering control strategies. After conducting simulation analysis, benefits such as reduced total delay and increased total throughput were quantified. It was found that in most cases there was no metering rate that could simultaneously minimize the total delay and maximize the total throughput simultaneously. In general, the benefit for implementing either pre-timed control or demand/capacity control could be observed after comparing to no control situation. Future studies should be given to determine the best situations (the range of traffic volumes) for applying the pre-timed and demand/capacity control.

The analysis conducted in this part demonstrated that ramp metering control is a potential strategy to improve traffic operations on the study site. In addition, an effective multi-ramp metering control algorithm, which will optimize time-dependent metering rates for multiple ramps is desired to be developed.

DYNAMIC MULTI-RAMP METERING CONTROL

In real world, traffic feeding into a freeway network varies over space and time. With the implementation of real-time ramp metering control, the traffic operations of the study site should be modeled in a dynamical way to reflect actual traffic and geometric situations.

Before developing the dynamic model for this study, it was found that the dynamic multi-ramp metering control problem was not only a time-varying but also a multivariate optimization problem. The objective is to optimize metering rates so as to maximize the total network throughput or minimize the total network delay subject to a set of constraints (e.g., meter locations, ramp storage capacities, lower and upper bounds of ramp metering rates). In order to achieve this objective, simultaneous perturbation stochastic approximation (SPSA) algorithm was introduced to optimize the developed dynamic multi-ramp metering control model. The model development, application and evaluation were analyzed with the use of CORSIM model developed in SIMULATION NETWORK MODELING. A procedure was designed in this part to accommodate dynamic change of metering rates during simulation.

Introduction

In the past, various ramp metering algorithms were designed and deployed. Based on different considerations, the algorithms were used to find reasonable metering rates through optimizing linear or nonlinear functions. With the development of real-time surveillance systems (e.g., various detectors that lead to an improvement in data collection and processing), and optimization skills (e.g., linear-quadratic optimization technique and hierarchical decomposition algorithm), solving a large-scale nonlinear optimization problem is no longer a difficult task. However, explicit relationships between adjustable or controllable system parameters and system performance have to be obtained in order to analyze detailed modeling information. Real-world systems are often too complex to allow such a detailed description.

In optimization problems, the gradient of the objective function with respect to the decision variables needs to be attained exactly, while the solution can be optimized by setting the gradient of the objective function equal to zero and solving it. However, the process to compute the gradient of a complicated objective function is often difficult. The SPSA algorithm has significant advantages in solving multivariate optimization problems whose gradient of the objective function is often difficult to be derived. Such advantage makes the SPSA an ideal candidate methodology to optimize the dynamic ramp metering control problem. In this study, SPSA was applied to optimize metering rates with the use of the microscopic traffic simulation model CORSIM.

SPSA Algorithm

The SPSA algorithm is a recursive optimization technique that was first introduced and developed by Spall.[39] Based on the measurement of the objective function (not on the measurement of the gradient of the objective function), SPSA is an easily implemented and highly efficient gradient approximation algorithm. The application of the SPSA algorithm to optimize the dynamic multi-ramp metering control problem is discussed below.

Let **L(λ)** with vector **λ** be the objective function to be optimized by a set of system optimized parameters **λ**. If **L(λ)** is a differentiable function with respect to **λ**, ***g*(λ)** represents the gradient of **L(λ)** and shown in Eq. 8.

$$g(\lambda)=\frac{\partial L(\lambda)}{\partial \lambda} \qquad (8)$$

Finding the approximate optimal solution of Eq. 8 is the major responsibility of SPSA. Assume that the measurement of the objective function **y(λ)** is represented by Eq. 9 for any **λ**:

$$y(\lambda) = L(\lambda)+noise \qquad (9)$$

The SPSA algorithm gives an initial guess of the optimal **λ** represented by $\hat{\lambda}_0$ and uses **y(λ)** to update **λ** recursively until the optimal solution λ_h^* is approximated. In the approximation process, SPSA iteratively produces a sequence of estimates (e.g., $\hat{\lambda}_0$, $\hat{\lambda}_1$, $\hat{\lambda}_2$, … , $\hat{\lambda}_{h+1}$) generated by the following steps. The configuration of the SPSA algorithm is shown in Figure 6.1.

Step 0: Initialization

Set counter ***h*** equal to 0. Pick initial guess $\hat{\lambda}_0$ and non-negative coefficients, **a**, **c**, **β** and **γ** in the SPSA gain sequences as shown in Eqs. 10 and 11. As a rule-of-thumb, a large **a** will enhance performance in the later iterations by producing a larger searching step size, while it will be effective to set **c** as smaller positive number. Choosing β ≤ 1.0 usually yields better finite-sample performance through maintaining a larger step size. Theoretically valid and recommended values for β and γ are 0.602 and 0.101, respectively. [41]

$$\mathbf{a}_h = \mathbf{a}(h + 1)^{-\beta} \tag{10}$$

$$\mathbf{c}_h = \mathbf{c}(h + 1)^{-\gamma} \tag{11}$$

Step 1: Generate Simultaneous Perturbation Vector

A ***p***-dimensional random vector $\mathbf{\Delta}_h$ is developed, where each of the components is independently generated from a zero-mean probability distribution. An effective (and theoretically valid) choice for each component of $\mathbf{\Delta}_h$ is to use a Bernoulli ±1 distribution with probability of ½ for each ±1 outcome. Since uniform and normal random variables have infinite inverse moments, they are not allowed for the elements of $\mathbf{\Delta}_h$.

Step 2: Evaluate Objective Function.

Estimate two measurements of the objective function **L(λ)** based on a simultaneous perturbation around the current $\hat{\lambda}_h$ **(**e.g., **y(**$\hat{\lambda}_h$ **+ c_h Δ_h)** and **y(**$\hat{\lambda}_h$ **- c_h Δ_h))** where **c_h** and **Δ_h** can be obtained from Steps 0 and 1, respectively.

Step 3: Approximate Gradient.

Generate the simultaneous perturbation approximation to the (unknown) ***p***-dimensional gradient $\hat{g}(\hat{\lambda}_h)$ **:**

$$\hat{g}(\hat{\lambda}_h) = \begin{bmatrix} \dfrac{y(\hat{\lambda}_h + c_h \Delta_h) - y(\hat{\lambda}_h - c_h \Delta_h)}{2\, c_h\, \Delta_{h1}} \\ \dfrac{y(\hat{\lambda}_h + c_h \Delta_h) - y(\hat{\lambda}_h - c_h \Delta_h)}{2\, c_h\, \Delta_{h2}} \\ \\ \dfrac{y(\hat{\lambda}_h + c_h \Delta_h) - y(\hat{\lambda}_h - c_h \Delta_h)}{2\, c_h\, \Delta_{hp}} \end{bmatrix} \qquad (12)$$

where **Δ_{hi}** is the i^{th} component of the **Δ_h** vector.

Step 4: Update $\hat{\lambda}_h$

Use the standard stochastic approximation form

$$\hat{\lambda}_{h+1} = \hat{\lambda}_h - \mathbf{a}_h \hat{g}(\hat{\lambda}_h) \qquad (13)$$

to replace $\hat{\lambda}_h$ by $\hat{\lambda}_{h+1}$**.**

Step 5: Iteration or Termination

Return to Step 1 and increase the counter from ***h*** to ***h+1***. Terminate the algorithm if the difference between successive iterations is less than a pre-set value that should be small enough to guarantee the accuracy; and the $\hat{\lambda}_h$ found in the last iteration is the optimum, called $\overset{*}{\lambda}_h$.

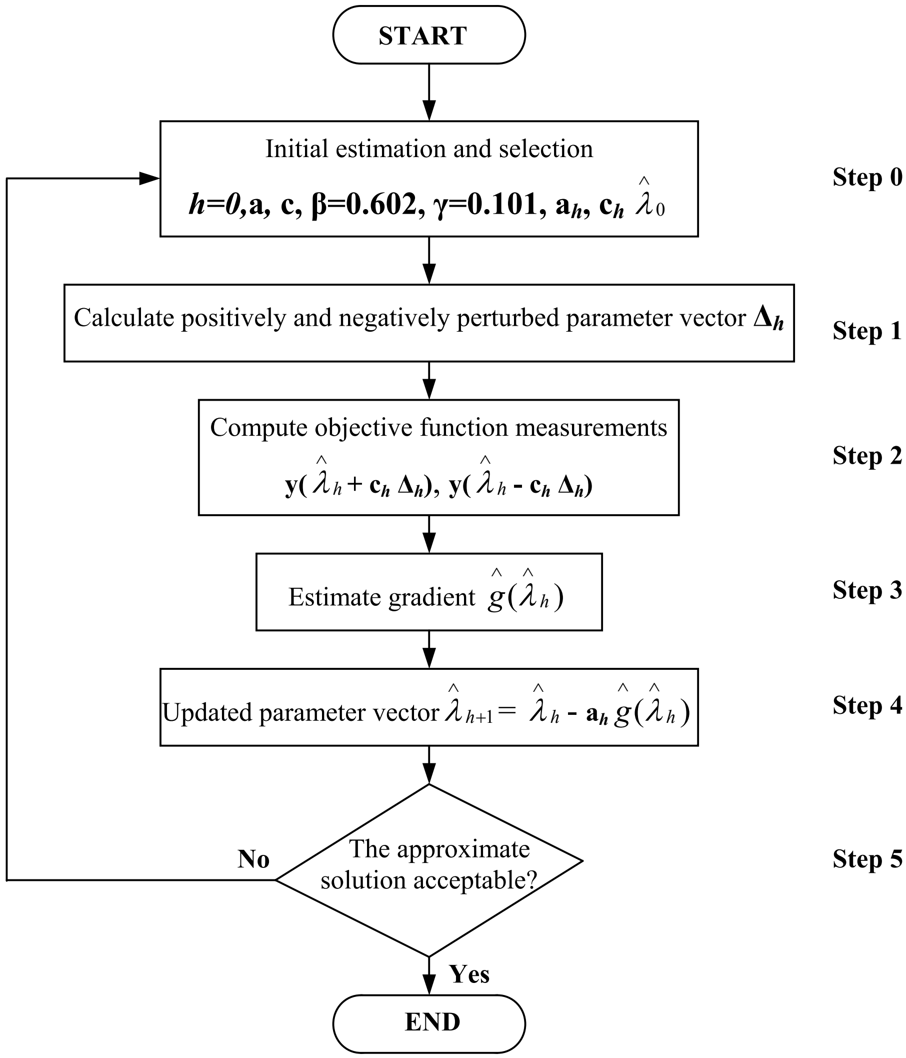

Figure 6.1 - The SPSA Algorithm

Model Formulation

Before applying SPSA in optimizing ramp metering rates, the objective function should be formulated. The goal of ramp metering control is to alleviate freeway congestion and improve its operational performance. Several MOEs (e.g., total delay, total vehicle-miles, total traffic throughput (*TTT*), etc.) can be candidate objectives to be optimized. The total traffic throughput is relatively more appealing than others, since the number of discharged vehicles from a freeway system can be easily detected in practice. The total throughput was thus selected as the objective to be maximized in this study.

In order to develop a ramp metering control model, a freeway including N segments with multiple on-ramps and off-ramps was assumed and shown in Figure 6.2. Note that the traffic volume varies over equal time phases. Thus, the control time period is a series of equal intervals. The dynamic equation of link density $\rho_i(k)$ (vehs/mi/ln)can be formulated as Eq. 14.

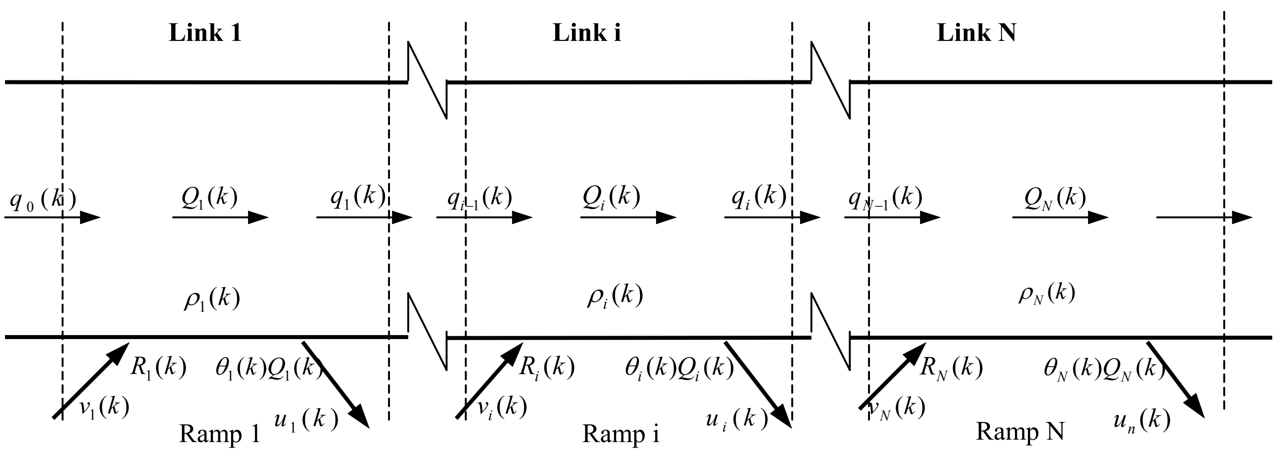

Figure 6.2 - General Freeway Network

$$\rho_i(k) = \rho_i(k-1) + [q_{i-1}(k) + \delta_i^{on} R_i(k) - \delta_i^{off} \theta_i(k) Q_i(k) - q_i(k)]T / L_i l_i$$

for i = 1, 2, …, N (14)

where $q_i(k)$: the volume entering link i+1 from link i during interval k, (vph);

$R_i(k)$: the metering rate for an on ramp of link i during interval k, (vph);

$Q_i(k)$: the mean flow rate of freeway link i during interval k, (vph);

δ_i^{on} : equal to 1 if an on-ramp of link i exists, otherwise equal to 0;

δ_i^{off} : equal to 1 if an off-ramp of link i exists, otherwise equal to 0;

$\theta_i(k)$: the turning percentage of traffic to the off ramp of link *i* during interval *k,* (%);

$v_i(k)$: the volume entering on-ramp of link *i* during interval *k*, (vph);

$u_i(k)$: the volume exiting off-ramp of link *i* during interval *k*, (vph);

T : the duration of a time interval, (hours);

L_i : the physical length of link *i*, (miles);

l_i : the number of through lanes of link *i*.

Eq. 14 shows that the projected mean density $\rho_i(k)$ of time interval *k* is dependent on that of time interval *k-1 .* The transition flow rate, $q_i(k)$ can thus be approximately described by Eqs.15 and 16.

$$q_i(k) = \alpha_i(k)[1-\delta_i^{off}\theta_i(k)]Q_i(k) + [1-\alpha_i(k)][Q_{i+1}(k) - \delta_{i+1}^{on}R_{i+1}(k)]$$

for *i* = 1, 2, …, N-1, and (15)

$$q_N(k) = Q_N(k) - \delta_N^{off}\theta_N(k)Q_N(k)$$

for *i* = N (16)

where $\alpha_i(k)$ is a weighted parameter representing the interaction between flows of links *i* and *i*+1 during interval *k.* The value of 0.5 set for $\alpha_i(k)$ can indicate the same influence to flows of links *i* and *i*+1.

Thus, by substituting Eqs. 15 and 16 into Eq. 14, Eqs. 17, 18 and 19 representing density functions for links from 1 to N can be derived.

$$\rho_1(k) = \rho_1(k-1) + [T/(L_1l_1)]q_0(k) + [T/(L_1l_1)][\alpha_1(k) - \delta_1^{off}\theta_1(k) + \delta_1^{off}\alpha_1(k)\theta_1(k)]Q_1(k)$$
$$+ [T/(L_1l_1)][\alpha_1(k)-1]Q_2(k) + [T/(L_1l_1)]\delta_1^{on}R_1(k) + [T/(L_1l_1)]\delta_2^{on}[1-\alpha_1(k)]R_2(k),$$

(17)

$$\rho_i(k) = \rho_i(k-1) + [T/(L_il_i)]\alpha_{i-1}(k)[1-\delta_{i-1}^{off}\theta_{i-1}(k)]Q_{i-1}(k) + [T/(L_il_i)]\{1-\alpha_{i-1}(k)$$

$$-\alpha_i(k) - \delta_i^{off}[1-\alpha_i(k)]\theta_i(k)\}Q_i(k) + [T/(L_i l_i)][\alpha_i(k)-1]Q_{i+1}(k)$$

$$+[T/(L_i l_i)]\alpha_{i-1}(k)\delta_i^{on}R_i(k) + [T/(L_i l_i)][1-\alpha_i(k)]\delta_{i+1}^{on}R_{i+1}(k)$$

for i = 2, 3, …, N-1, and (18)

$$\rho_N(k) = \rho_N(k-1) + [T/(L_N l_N)]\alpha_{N-1}(k)[1-\delta_{N-1}^{off}\theta_{N-1}(k)]Q_N(k)$$

$$-[T/(L_N l_N)]\alpha_{N-1}(k)Q_N(k) + [T/(L_N l_N)]\alpha_{N-1}(k)\delta_N^{on}R_N(k) \quad (19)$$

A nonlinear relationship between flow and density can be assumed by Eq. 20. [26]

$$Q_i(k) = \rho_i(k)S_i(k) \quad (20)$$

where $S_i(k)$ represents the mean speed of link i during interval k , which can be estimated by analyzing individual vehicle speeds collected by detectors.

The objective total traffic throughput (*TTT)* defined as the total number of vehicles discharging from the freeway section over the control period (Chang, el at. 1994b) is derived as

$$TTT = \sum_k \left[\sum_{i=1}^{N-1} \delta_i^{off}\theta_i(k)Q_i(k) + Q_N(K) \right] T \quad (21)$$

By substituting Eq. 20 into Eq.21, *TTT* is

$$TTT = T\sum_k \left[\sum_{i=1}^{N-1} \delta_i^{off}\theta_i(k)\rho_i(k)S_i(k) + \rho_N(k)S_N(k) \right] \quad (22)$$

One of the most important objectives of this study is to maximize (*TTT).* However, the nature of SPSA was designed to minimize an objective function. Thus, the objective function **L(λ)** will be reformulated as a large positive number *Z* minus *TTT*:

$$\mathbf{L(\lambda) = Z} - T\sum_k \left[\sum_{i}^{N-1} \delta_i^{off}\theta_i(k)\rho_i(k)S_i(k) + \rho_N(k)S_N(k) \right] \quad (23)$$

where **λ** is a set of variables $R_i(k)$ and $Q_i(k)$ that are considered as optimizable decision variables. In Eqs. 18, 19, 20 and 23, geometric parameters such as Z, N, δ_i^{on} , δ_i^{off} , $\alpha_i(k)$, T, L_i, and l_i can be collected from the analyzed freeway, while $\theta_i(k)$, $\rho_i(k-1)$, $q_o(k)$ and $S_i(k)$ can be either detected from sensors or estimated from historical data.

Dynamic Ramp Metering Control

In this section, a real-time ramp metering control model integrated with SPSA algorithm was developed, tested, and evaluated on single and multiple ramps. The before and after analysis was conducted.

Ramp Metering Control Model

The configuration of a system-wide multi-ramp metering control model was developed and shown in Figure 6.3. It could dynamically optimize ramp metering rates with the use of the SPSA algorithm, subject to a set of constraints discussed on pages 50 - 53.

According to the ramp storage capacity, the minimum ramp metering rate for each metered ramp could be estimated by Eq. 7 on page 52, while the maximum metering rate for each metered ramp was assumed to be 900 vphpl, based on the minimum metering headway of 4 seconds. The feasible range of metering rates for each metered ramp could thus be determined.

The ramp metering rates could be optimized by the SPSA algorithm discussed on pages 70 - 73, while considering dynamic traffic conditions and various constraints (e.g. on-ramp volumes, mainline capacity, the boundaries of feasible metering rates and ramp storage, etc.). The input data for optimizing metering rates could be obtained from the simulation results. The optimized metering rates obtained in the current time period were applied into the next simulation time period.

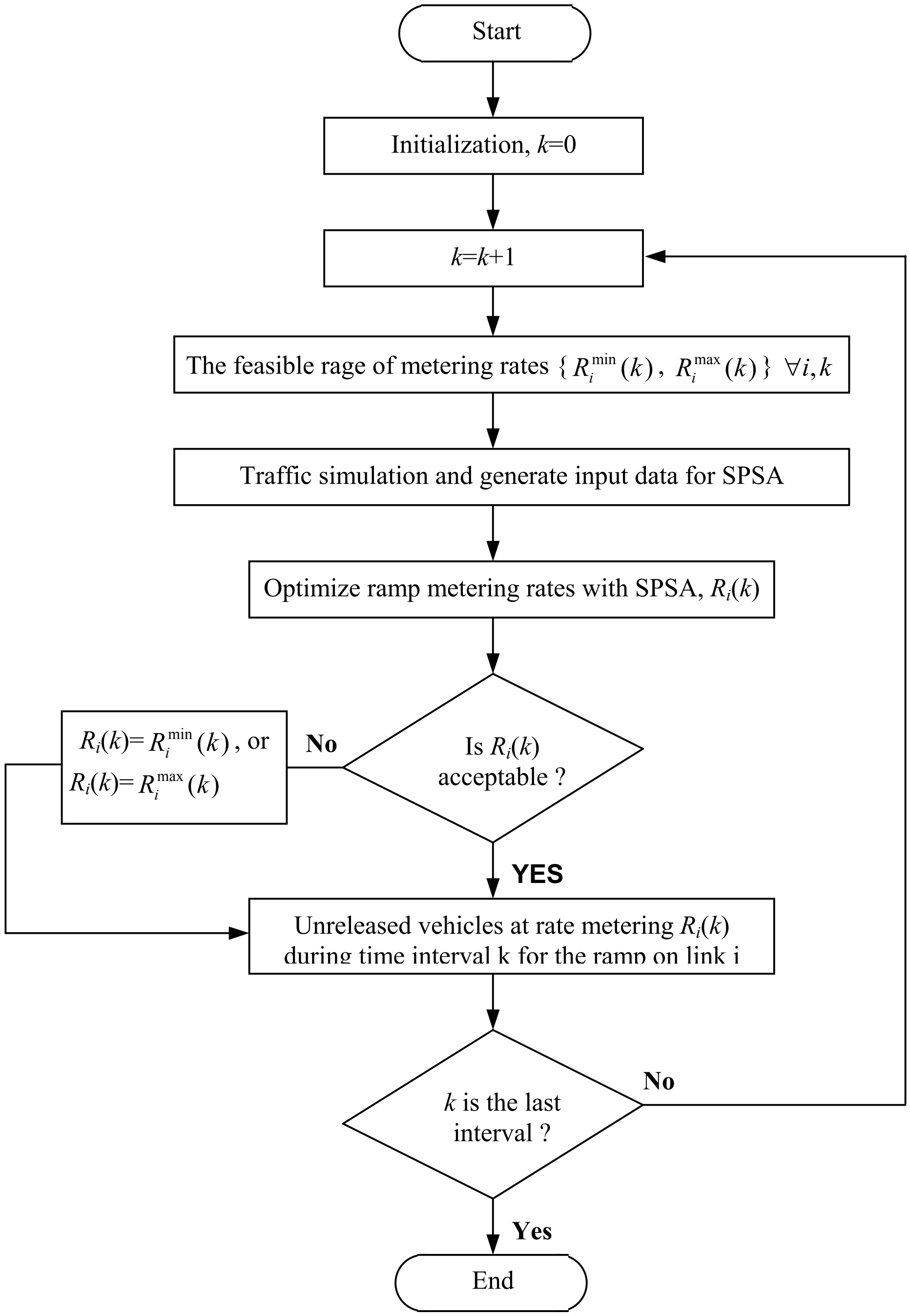

Figure 6.3 - Real-time Metering Control Model

Single Ramp Metering Control with SPSA

In order to test the developed real-time control model on I-80, the potential ramps suitable for metering control were identified in Simulation Analysis and Evaluation. Considering the proposed dynamic system control in real-time application, the time dependent demand of I-80 over a series of time intervals was simulated with CORSIM. In this study, the traffic operations (with and without the proposed system control) of 16 time intervals with 3-min duration of each interval were simulated.

The simulated entry traffic distribution is shown in Table 6.1. In order to find a feasible range of metering rates and conduct sensitive analyses, the entry flow (at link 300-301) increased in 200 vph per the time interval with fixed demands at on-ramps, while the percentage in the O/D matrix was kept unchanged.

Table 6.1 Traffic Demand Distribution

Time Interval*	Entry Flow	Node306	Node 307	Node 345	Node 356	Node 376	Node 377	Node 395
	vph							
1	2960	360	489	2159	819	400	1216	430
2	3160							
3	3360							
4	3560							
5	3760							
6	3960							
7	4160							
8	4360							
9	4560							
10	4760							
11	4960							
12	5160							
13	5360							
14	5560							
15	5760							
16	5960							

*: The duration of each time interval is 3 minutes.

As discussed from pages 73 to 77, the density of link *i* in interval *k* can be determined by $\rho_i(k-1)$ and other parameters presented in Eqs. 17, 18 and 19, which should not exceed the maximum value 45 vehs/mi/ln (*Highway Capacity Manual,* 1997) when the free flow speed is 65 mph. If $\rho_i(k)$ is greater than 45 vehs/ln-mile, the $R_i(k)$ is set default as $R_i^{\min}(k)$.

A computer program coded in FORTRAN was developed to optimize ramp metering rates with SPSA by minimizing the objective function as formulated in Eq. 23. The input data (e.g. $\theta_i(k)$, $\rho_i(k-1)$, $q_0(k)$, $S_i(k)$, $Q_i(k)$ and $R_i(K)$) either were initialized at the beginning time interval, or could be collected in real-time, or estimated from historical data. While executing the program to optimize metering rate for each ramp, parameters (e.g., **a** and **c)** in SPSA were iteratively updated to approximate the optimal solution. The optimal metering rates (in vph) for all single ramps over 16 time intervals are summarized in Table 6.2. Note that, while optimizing the metering rate for a ramp, other ramps were not under meter control.

Table 6.2 Optimal Metering Rates of Each Ramp from SPSA

Time Interval*	**Node 306**	**Node 307**	**Node 356**	**Node 376**	**Node 395**
	Vph				
1	705	794	895	737	766
2	705	794	895	737	766
3	705	794	895	737	766
4	720	815	900	753	783
5	735	836	900	771	802
6	751	858	900	789	822
7	767	881	900	808	842
8	779	881	900	820	842
9	779	881	900	820	842
10	779	881	900	820	842
11	779	881	900	820	842
12	779	881	900	820	842
13	779	881	900	820	842
14	779	881	886	819	774
15	779	881	874	758	761
16	779	881	862	744	748

*: The duration of each time interval is 3 minutes.

As mentioned earlier, the optimal metering rate obtained in each interval was based on the simulation output generated in the previous time interval. Thus, a shorter time interval could increase the precision of the control, but the computation effort increased as well. In reality, an appropriate length of the interval is desired to apply. Thus, the optimal benefit of ramp metering control can be achieved.

The output data (e.g., link volume, accumulated vehicle-mile and average delay of the whole network) for each time interval were collected. Since CORSIM only generated accumulated statistics, the MOEs in each interval could not be observed. A macro in MS-Excel was developed to efficiently retrieve data from simulation results, while the net benefit of each interval was estimated. Two MOEs, total delay and total throughput were selected for evaluating the benefit of ramp metering control. The total delay (veh-min) of the whole network was obtained from vehicle-mile (veh-mi) multiplied by average delay (min/mi), while the total throughput was obtained by summing the exiting volumes. Results are summarized in Tables 6.3 and 6.4 and shown in Figures 6.4 through 6.8.

Table 6.3 Total Throughput under Single Ramp Metering Control (SPSA)

Time Interval	**Entry Flow** (vph)	**Before** (veh/3min)	**After** (veh/3min)				
			Node 306	**Node 307**	**Node 356**	**Node 376**	**Node 395**
1	2960	467	445	430	437	441	449
2	3160	492	451	473	456	447	458
3	3360	437	459	477	481	469	454
4	3560	448	473	471	460	476	451
5	3760	438	484	465	457	455	485
6	3960	422	452	459	482	476	472
7	4160	442 (0%)	478 (8.14%)	459 (3.85%)	465 (5.20%)	475 (7.47%)	473 (7.01%)
8	4360	448	461	476	469	483	467
9	4560	450	484	446	468	445	464
10	4760	482	463	487	495	475	479
11	4960	498	489	478	489	478	491
12	5160	512	489	486	483	515	485
13	5360	509	530	516	493	506	501
14	5560	532	499	525	510	517	516
15	5760	537	503	523	518	495	529
16	5960	542	527	516	503	523	509
Total (1-16)		7656	7686	7687	7665	7675	7682
%			0.39	0.40	0.11	0.25	0.34
Total (3-9)		**3085**	**3289**	**3253**	**3282**	**3278**	**3265**
%			**6.63**	**5.46**	**6.37**	**6.27**	**5.84**

Table 6.4 Total Delay under Single Ramp Metering Control (SPSA)

Time Interval	Entry Flow (vph)	Before (veh-min)	After (veh-min)				
			Node 306	Node 307	Node 356	Node 376	Node 395
1	2960	614.5	595.2	613.8	623.0	627.6	617.4
2	3160	619.7	652.8	620.7	647.7	629.3	607.0
3	3360	560.3	624.9	601.7	605.5	637.9	637.4
4	3560	655.0	590.5	530.0	642.6	628.4	682.7
5	3760	624.0	540.4	575.8	648.0	603.1	599.0
6	3960	527.2	629.1	558.8	667.5	605.7	645.2
7	4160	623.9	672.2	674.2	639.9	645.0	674.0
8	4360	742.5	678.8	650.9	692.9	682.8	744.0
9	4560	836.0	669.6	825.9	813.3	728.5	754.9
10	4760	981.4	948.1	850.3	820.3	930.6	785.9
11	4960	973.0	876.9	936.7	953.4	892.5	903.1
12	5160	1170.2	966.5	1081.1	1071.7	1024.0	1092.8
13	5360	1278.9	1053.9	1112.8	1089.5	1076.1	1102.5
14	5560	1338.6	1251.2	1185.5	1249.6	1230.4	1295.3
15	5760	1469.0	1349.1	1350.4	1382.4	1412.7	1281.8
16	5960	1554.1	1702.0	1484.8	1615.2	1462.1	1618.2
Total (1-16)		14568.2	13801.3	13653.3	14162.5	13816.5	14041.5
%			-5.26	-6.28	-2.78	-5.16	-3.62
Total (3-9)		4568.8	4405.6	4417.2	4709.6	4531.3	4737.3
%			-3.57	-3.32	3.08	-0.82	3.69
Total (8-15)		**10343.6**	**9496.2**	**9478.4**	**9688.3**	**9439.6**	**9578.7**
%			**-8.92**	**-9.13**	**-6.76**	**-9.58**	**-7.99**

*: The duration of each time interval is 3 minutes for Table 6.3 and 6.4.

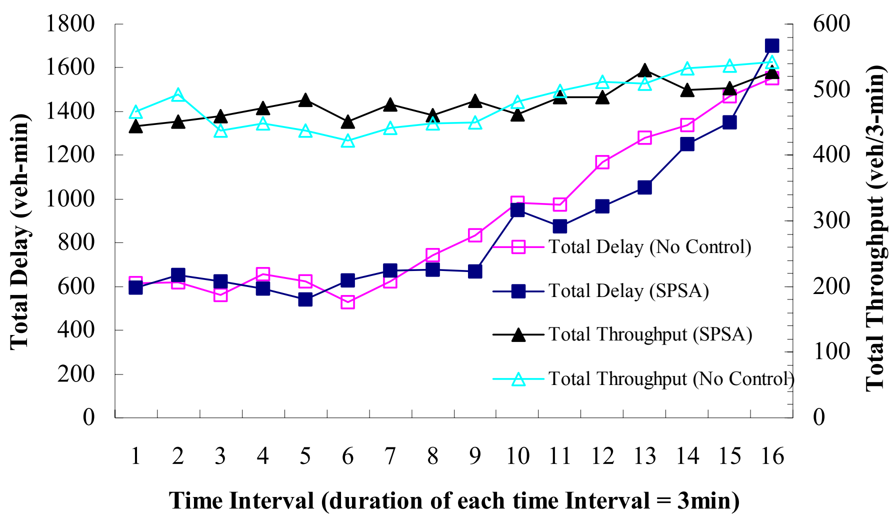

Figure 6.4 - Total Delay and Total Throughput over Time (SPSA Control at Node 306)

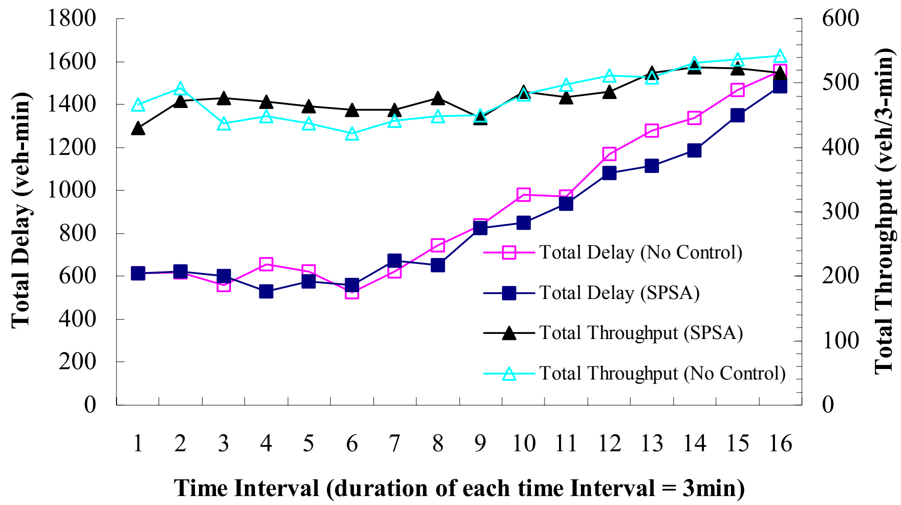

Figure 6.5 - Total Delay and Total Throughput over Time (SPSA Control at Node 307)

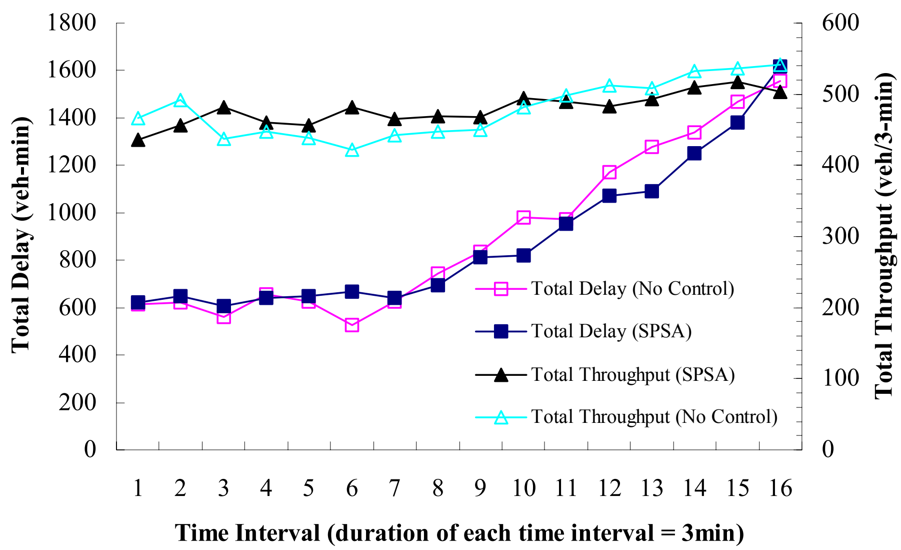

Figure 6.6 - Total Delay and Total Throughput over Time (SPSA Control at Node 356)

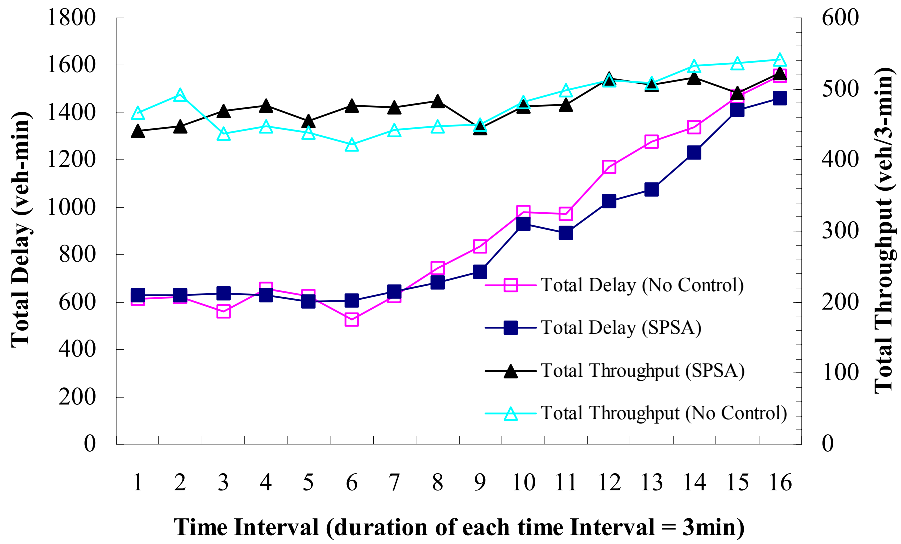

Figure 6.7 - Total Delay and Total Throughput over Time (SPSA Control at Node 376)

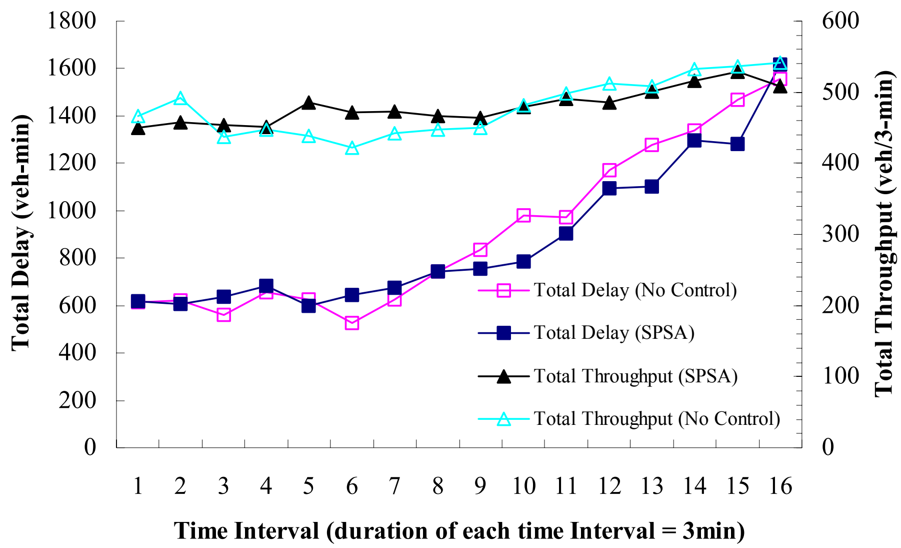

Figure 6.8 - Total Delays and Total Throughput over Time (SPSA Control at Node 395)

With the application of the developed dynamic multi-ramp metering control model to each individual ramp, e.g., at node 306, simulation results (Table 6.3 and Figure 6.4) showed that the total throughput (from time interval 3 to 9) could be increased by 6.63% (from 3085 veh to 3289 veh). However, the increased total throughput was increased by only 0.39% for all 16 time intervals. This analysis demonstrates that the developed dynamic SPSA ramp metering control could be efficient, while the entry flow ranged from 3360 vph to 4560 vph.

Table 6.4 and Figure 6.4 show the total delay while node 306 was under metering control. It was found that the total delays were reduced from the eighth to the fifteenth time interval. After control, the reduction of the total delay was 8.92% for the eight time intervals and 5.26% for all 16 time intervals. Thus, the proposed metering control at node 306 could produce benefit, while the entry flow ranged between 4360 and 5760 vph.

For other metered ramps (e.g., nodes 307, 356, 376 and 395), similar analysis was conducted. The suggested entry flows are shown in Table 6.5.

Table 6.5 Suggested Ranges of Entry Flows from Mainline under Single Ramp Metering Control (SPSA)

	Ramp Metering Control Node				
	306	**307**	**356**	**376**	**395**
Increasing Total Throughput	3360~4560 vph	3360~4560 vph	3360~4560 vph	3360~4560 vph	3360~4560 vph
Reducing Total Delay	4360~5760 vph	4360~5960 vph or more	4360~5760 vph	4360~5960 vph or more	4360~5760 vph

<u>Dynamic Multiple Ramps Metering Control with SPSA</u>

In this section, the developed SPSA control would be applied simultaneously for multiple metered ramps (e.g., nodes 306, 307, 356, 376 and 395). Similar to the situation of single ramp control discussed on page 79, a 48-minute simulation duration was divided into 16 time intervals. The density constraint for single ramp control discussed on pages 79-80 also worked for multiple ramp control. Using the same example, the benefit of network-wide SPSA control could be evaluated.

The following scenarios were designed for the evaluation and sensitivity analysis, while the simulation results under single ramp metering control optimized individually on pages 81-82 were used for comparing that with simultaneous control.

Scenario A:

In this scenario, the optimal metering rates (shown in Table 6.2) were applied on the corresponding ramps. Therefore, the coordination among control of the five metered ramps was not considered.

Scenario B:

The metering rates applied in this scenario were jointly optimized with the developed SPSA algorithm. The coordination among all controlled ramps was considered to achieve the ultimate benefit for the analyzed network. The optimal metering rates over time are shown in Table 6.6.

Scenarios C, D, E, F and G:

Five scenarios, designed to compare the efficiency of multiple ramp control with SPSA (Scenario B) and investigate the sensitivity of metering rate variation at ramps, were derived from Scenario A. In these scenarios, the adjustment metering rates were different from ramp to ramp, which are shown in Tables 6.7 through 6.12.

For example, the scenario C shown in Table 6.7 represents that the metering rates at all metered ramps in every time interval were increased (Table 6.8) based on the optimal metering rates summarized in Table 6.2. In scenario D, the adjusted ramp metering rates at nodes 306, 307 and 356 increased, while that at nodes 376 and 395 decreased (Table 6.9) from the optimal rates shown in Table 6.2. Scenarios E, F, and G (Tables 6.10, 6.11, and 6.12) could be interpreted in the same manner.

Table 6.6 Jointly Optimal Ramp Metering Rates (vph) with SPSA

Time Interval*	Node 306	Node 307	Node 356	Node 376	Node 395
	Metering Rate, vph (**Headway**, seconds)				
1	650 (5.54)	766 (4.70)	900 (4.00)	753 (4.78)	799 (4.51)
2	650 (5.54)	766 (4.70)	900 (4.00)	753 (4.78)	799 (4.51)
3	650 (5.54)	766 (4.70)	900 (4.00)	753 (4.78)	799 (4.51)
4	664 (5.42)	766 (4.70)	900 (4.00)	769 (4.68)	816 (4.41)
5	680 (5.29)	766 (4.70)	900 (4.00)	787 (4.57)	835 (4.31)
6	696 (5.17)	776 (4.64)	900 (4.00)	805 (4.47)	855 (4.21)
7	712 (5.06)	799 (4.51)	900 (4.00)	824 (4.37)	875 (4.11)
8	724 (4.97)	799 (4.51)	900 (4.00)	824 (4.37)	875 (4.11)
9	723 (4.98)	799 (4.51)	900 (4.00)	824 (4.37)	875 (4.11)
10	719 (5.01)	754 (4.77)	900 (4.00)	900 (4.00)	889 (4.05)
11	713 (5.05)	747 (4.82)	900 (4.00)	900 (4.00)	900 (4.00)
12	709 (5.08)	742 (4.85)	900 (4.00)	900 (4.00)	900 (4.00)
13	705 (5.11)	737 (4.88)	891 (4.04)	900 (4.00)	900 (4.00)
14	693 (5.19)	721 (4.99)	881 (4.09)	900 (4.00)	900 (4.00)
15	681 (5.29)	705 (5.11)	869 (4.14)	867 (4.15)	900 (4.00)
16	668 (5.39)	689 (5.22)	860 (4.19)	887 (4.06)	900 (4.00)

*: The duration of each time interval is 3 minutes.

Table 6.7 Test Scenarios C, D, E, F and G

Scenario	Node 306	Node 307	Node 356	Node 376	Node 395
	Adjustment Guideline for Metering Rates in Scenario A				
C	Up	Up	Up	Up	Up
D	Up	Up	Up	Down	Down
E	Up	Down	Up	Up	Down
F	Down	Up	Up	Down	Up
G	Up	Down	Up	Up	Up

Table 6.8 Ramp Metering Rates (vph) in Scenario C

Time Interval*	Node 306	Node 307	Node 356	Node 376	Node 395
	Metering Rate, vph (**Headway**, seconds)				
1	727 (4.95)	808 (4.46)	900 (4.00)	753 (4.78)	799 (4.51)
2	727 (4.95)	808 (4.46)	900 (4.00)	753 (4.78)	799 (4.51)
3	727 (4.95)	808 (4.46)	900 (4.00)	753 (4.78)	799 (4.51)
4	741 (4.86)	829 (4.34)	900 (4.00)	769 (4.68)	816 (4.41)
5	757 (4.76)	850 (4.24)	900 (4.00)	787 (4.57)	835 (4.31)
6	773 (4.66)	872 (4.13)	900 (4.00)	805 (4.47)	855 (4.21)
7	789 (4.56)	895 (4.02)	900 (4.00)	824 (4.37)	875 (4.11)
8	801 (4.49)	895 (4.02)	900 (4.00)	824 (4.37)	875 (4.11)
9	800 (4.50)	895 (4.02)	900 (4.00)	824 (4.37)	875 (4.11)
10	796 (4.52)	850 (4.24)	900 (4.00)	900 (4.00)	889 (4.05)
11	790 (4.56)	843 (4.27)	900 (4.00)	900 (4.00)	900 (4.00)
12	783 (4.60)	838 (4.30)	900 (4.00)	900 (4.00)	900 (4.00)
13	782 (4.60)	833 (4.32)	891 (4.04)	900 (4.00)	900 (4.00)
14	770 (4.68)	817 (4.41)	893 (4.03)	900 (4.00)	900 (4.00)
15	758 (4.75)	801 (4.49)	881 (4.09)	867 (4.15)	900 (4.00)
16	745 (4.83)	785 (4.59)	869 (4.14)	887 (4.06)	900 (4.00)

*: The duration of each time interval is 3 minutes.

Table 6.9 Ramp Metering Rates (vph) in Scenario D

Time Interval*	Node 306	Node 307	Node 356	Node 376	Node 395
	Metering Rate, vph (**Headway**, seconds)				
1	727 (4.95)	808 (4.46)	900 (4.00)	702 (5.13)	749 (4.81)
2	727 (4.95)	808 (4.46)	900 (4.00)	702 (5.13)	749 (4.81)
3	727 (4.95)	808 (4.46)	900 (4.00)	702 (5.13)	749 (4.81)
4	741 (4.86)	829 (4.34)	900 (4.00)	718 (5.01)	766 (4.70)
5	757 (4.76)	850 (4.24)	900 (4.00)	736 (4.89)	785 (4.59)
6	773 (4.66)	872 (4.13)	900 (4.00)	754 (4.77)	805 (4.47)
7	789 (4.56)	895 (4.02)	900 (4.00)	773 (4.66)	825 (4.36)
8	801 (4.49)	895 (4.02)	900 (4.00)	773 (4.66)	825 (4.36)
9	800 (4.50)	895 (4.02)	900 (4.00)	773 (4.66)	825 (4.36)
10	796 (4.52)	850 (4.24)	900 (4.00)	900 (4.00)	836 (4.31)
11	790 (4.56)	843 (4.27)	900 (4.00)	900 (4.00)	900 (4.00)
12	783 (4.60)	838 (4.30)	900 (4.00)	900 (4.00)	900 (4.00)
13	782 (4.60)	833 (4.32)	891 (4.04)	900 (4.00)	900 (4.00)
14	770 (4.68)	817 (4.41)	893 (4.03)	900 (4.00)	900 (4.00)
15	758 (4.75)	801 (4.49)	881 (4.09)	887 (4.06)	900 (4.00)
16	745 (4.83)	785 (4.59)	869 (4.14)	865 (4.16)	900 (4.00)

*: The duration of each time interval is 3 minutes.

Table 6.10 Ramp Metering Rates (vph) in Scenario E

Time Interval*	Node 306	Node 307	Node 356	Node 376	Node 395
	Metering Rate, vph (**Headway**, seconds)				
1	727 (4.95)	766 (4.70)	900 (4.00)	753 (4.78)	749 (4.81)
2	727 (4.95)	766 (4.70)	900 (4.00)	753 (4.78)	749 (4.81)
3	727 (4.95)	766 (4.70)	900 (4.00)	753 (4.78)	749 (4.81)
4	741 (4.86)	766 (4.70)	900 (4.00)	769 (4.68)	766 (4.70)
5	757 (4.76)	766 (4.70)	900 (4.00)	787 (4.57)	785 (4.59)
6	773 (4.66)	776 (4.64)	900 (4.00)	805 (4.47)	805 (4.47)
7	789 (4.56)	799 (4.51)	900 (4.00)	824 (4.37)	825 (4.36)
8	801 (4.49)	799 (4.51)	900 (4.00)	824 (4.37)	825 (4.36)
9	800 (4.50)	799 (4.51)	900 (4.00)	824 (4.37)	825 (4.36)
10	796 (4.52)	754 (4.77)	900 (4.00)	900 (4.00)	836 (4.31)
11	790 (4.56)	747 (4.82)	900 (4.00)	900 (4.00)	900 (4.00)
12	783 (4.60)	742 (4.85)	900 (4.00)	900 (4.00)	900 (4.00)
13	782 (4.60)	737 (4.88)	891 (4.04)	900 (4.00)	900 (4.00)
14	770 (4.68)	721 (4.99)	893 (4.03)	900 (4.00)	900 (4.00)
15	758 (4.75)	705 (5.11)	881 (4.09)	867 (4.15)	900 (4.00)
16	745 (4.83)	689 (5.22)	869 (4.14)	887 (4.06)	900 (4.00)

*: The duration of each time interval is 3 minutes.

Table 6.11 Ramp Metering Rates (vph) in Scenario F

Time Interval*	Node 306	Node 307	Node 356	Node 376	Node 395
	Metering Rate, vph (**Headway**, seconds)				
1	650 (5.54)	808 (4.46)	900 (4.00)	702 (5.13)	799 (4.51)
2	650 (5.54)	808 (4.46)	900 (4.00)	702 (5.13)	799 (4.51)
3	650 (5.54)	808 (4.46)	900 (4.00)	702 (5.13)	799 (4.51)
4	664 (5.42)	829 (4.34)	900 (4.00)	718 (5.01)	816 (4.41)
5	680 (5.29)	850 (4.24)	900 (4.00)	736 (4.89)	835 (4.31)
6	696 (5.17)	872 (4.13)	900 (4.00)	754 (4.77)	855 (4.21)
7	712 (5.06)	895 (4.02)	900 (4.00)	773 (4.66)	875 (4.11)
8	724 (4.97)	895 (4.02)	900 (4.00)	773 (4.66)	875 (4.11)
9	723 (4.98)	895 (4.02)	900 (4.00)	773 (4.66)	875 (4.11)
10	719 (5.01)	850 (4.24)	900 (4.00)	900 (4.00)	889 (4.05)
11	713 (5.05)	843 (4.27)	900 (4.00)	900 (4.00)	900 (4.00)
12	709 (5.08)	838 (4.30)	900 (4.00)	900 (4.00)	900 (4.00)
13	705 (5.11)	833 (4.32)	891 (4.04)	900 (4.00)	900 (4.00)
14	693 (5.19)	817 (4.41)	893 (4.03)	900 (4.00)	900 (4.00)
15	681 (5.29)	801 (4.49)	881 (4.09)	887 (4.06)	900 (4.00)
16	668 (5.39)	785 (4.59)	869 (4.14)	865 (4.16)	900 (4.00)

*: The duration of each time interval is 3 minutes.

Table 6.12 Ramp Metering Rates (vph) in Scenario G

Time Interval*	Node 306	Node 307	Node 356	Node 376	Node 395
	Metering Rate, vph (**Headway**, seconds)				
1	727 (4.95)	766 (4.70)	900 (4.00)	753 (4.78)	799 (4.51)
2	727 (4.95)	766 (4.70)	900 (4.00)	753 (4.78)	799 (4.51)
3	727 (4.95)	766 (4.70)	900 (4.00)	753 (4.78)	799 (4.51)
4	741 (4.86)	766 (4.70)	900 (4.00)	769 (4.68)	816 (4.41)
5	757 (4.76)	766 (4.70)	900 (4.00)	787 (4.57)	835 (4.31)
6	773 (4.66)	776 (4.64)	900 (4.00)	805 (4.47)	855 (4.21)
7	789 (4.56)	799 (4.51)	900 (4.00)	824 (4.37)	875 (4.11)
8	801 (4.49)	799 (4.51)	900 (4.00)	824 (4.37)	875 (4.11)
9	800 (4.50)	799 (4.51)	900 (4.00)	824 (4.37)	875 (4.11)
10	796 (4.52)	754 (4.77)	900 (4.00)	900 (4.00)	889 (4.05)
11	790 (4.56)	747 (4.82)	900 (4.00)	900 (4.00)	900 (4.00)
12	783 (4.60)	742 (4.85)	900 (4.00)	900 (4.00)	900 (4.00)
13	782 (4.60)	737 (4.88)	891 (4.04)	900 (4.00)	900 (4.00)
14	770 (4.68)	721 (4.99)	893 (4.03)	900 (4.00)	900 (4.00)
15	758 (4.75)	705 (5.11)	881 (4.09)	867 (4.15)	900 (4.00)
16	745 (4.83)	689 (5.22)	869 (4.14)	887 (4.06)	900 (4.00)

*: The duration of each time interval is 3 minutes.

Results Analysis

The simulated data (e.g., accumulated link volumes, accumulated vehicle-miles, and accumulated delay) were collected and processed to generate MOEs for each interval. The data analysis process was the same as that of single ramp control discussed from pages 79 to 81. Results are shown in Tables 6.13 and 6.14 and Figures 6.9 and 6.10.

Based on the existing traffic entry flow of 4160 vph at time interval 7 on mainline, the total throughput before control was 442 veh/3-min, while that of Scenario B was 482 veh/3-min (Table 6.13) with 9.05% increase and achieved the maximum benefit. Thus, the proposed dynamic multiple ramps control with SPSA might be efficient to improve traffic operation.

As shown in Table 6.13 and Figure 6.9, the total throughputs for Scenario A and Scenario B varied over time. Compared with no control situation from the third to ninth time interval, the accumulated total throughputs of Scenario A and Scenario B increased by 6.85 % and 8.07%, respectively. Thus, the benefit achieved by Scenario B was better than that by Scenario A during intervals 3 to 9. For Scenarios C through G, the accumulated total throughputs increased by 5.54%, 5.88%, 6.15%, 5.09% and 6.49 % during intervals 3 to 9, respectively. None of them was superior than either Scenario A or B. Therefore, Scenario B was the most efficient scenario in increasing total throughputs when the mainline traffic entry flow ranged from 3360 vph to 4560 vph.

Table 6.13 Total Throughputs vs. Control Scenarios

Interval *	Entry Flow (vph)	Before** (veh/3min)	Scenario (veh/3min)						
			A	B	C	D	E	F	G
1	2960	467	422	432	443	434	443	459	402
2	3160	492	452	431	462	458	462	459	481
3	3360	437	462	449	442	446	475	460	453
4	3560	448	441	475	472	483	473	462	480
5	3760	438	472	519	472	458	457	457	455
6	3960	422	480	447	479	465	456	441	476
7	**4160**	**442 (0%)**	**478 (8.14%)**	**482 (9.05%)**	**458 (3.62%)**	**473 (7.01%)**	**479 (8.37%)**	**478 (8.14%)**	**461 (4.30%)**
8	4360	448	468	487	475	473	458	477	474
9	4560	450	497	477	458	468	478	466	487
10	4760	482	473	494	482	456	489	482	467
11	4960	498	467	461	492	503	488	500	486
12	5160	512	505	454	490	499	482	482	497
13	5360	509	506	553	489	502	493	483	500
14	5560	532	525	516	504	504	494	500	517
15	5760	537	513	543	519	505	538	521	517
16	5960	542	556	529	521	531	515	540	513
Total (1-16)		7656	7715	7745	7658	7657	7678	7666	7666
%			0.77	1.16	0.02	0.02	0.28	0.13	0.13
Total (3-9)		**3085**	**3296**	**3334**	**3256**	**3266**	**3275**	**3242**	**3285**
%			**6.85**	**8.07**	**5.54**	**5.88**	**6.15**	**5.09**	**6.49**

*: The duration of each time Interval is 3 minutes. **: No control situation.

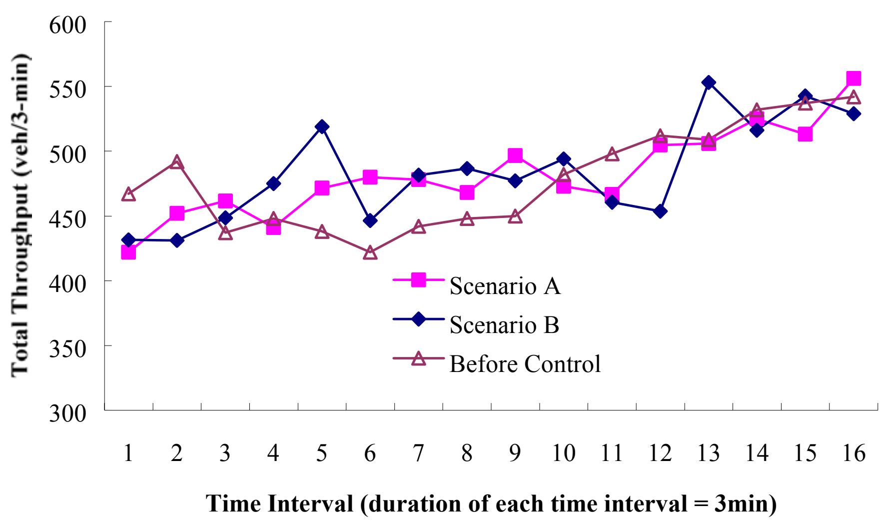

Figure 6.9 - Total Throughput Over Time (Scenarios A and B)

The accumulated total delay from the eighth to fifteenth time interval was 10343.6 vehicle-minutes before control. Scenario B reduced the accumulated total delay by 9.73% during the eight intervals (see Table 6.14 and Figure 6.10). In general, the accumulated total delays in Scenario B decreased 5.68 % after the application of metering control during 16 time intervals (48 minutes from interval 1 to interval 16), which implied that metering control was more effective when the mainline entry flow was between 4360 vph and 5760 vph.

Table 6.14 Total Delay vs. Control Scenarios

Interval *	Entry Flow (vph)	Before** (veh-min)	Scenario (veh-min) A	B	C	D	E	F	G
1	2960	614.5	629.0	603.7	599.1	617.4	643.5	594.6	657.3
2	3160	619.7	636.1	641.6	620.6	627.0	629.2	599.7	651.5
3	3360	560.3	616.5	623.7	631.6	641.4	621.0	609.6	646.3
4	3560	655.0	652.2	638.2	648.7	628.8	578.5	621.9	664.7
5	3760	624.0	642.0	610.3	572.9	586.5	617.6	638.5	660.9
6	3960	527.2	595.0	599.3	609.9	692.3	613.7	650.4	647.4
7	4160	623.9	625.3	687.6	680.5	595.5	642.8	737.4	659.0
8	4360	742.5	737.7	715.0	677.2	737.4	705.8	698.4	717.0
9	4560	836.0	810.5	719.8	793.4	855.7	792.4	780.6	742.1
10	4760	981.4	853.4	874.4	772.2	856.3	768.0	919.2	894.4
11	4960	973.0	1000.3	859.2	978.7	944.3	985.1	906.6	907.5
12	5160	1170.2	1003.3	1049.3	1054.2	1115.5	970.1	1142.7	1079.6
13	5360	1278.9	1093.3	1089.3	1154.6	1047.4	1115.1	1143.7	1059.2
14	5560	1338.6	1288.6	1184.9	1341.0	1251.2	1377.5	1311.0	1308.7
15	5760	1469.0	1369.0	1364.9	1431.4	1421.9	1366.9	1545.5	1332.4
16	5960	1554.1	1627.7	1480.0	1525.1	1519.1	1615.3	1545.4	1518.7
Total (1-16)		14568.2	14179.9	13741.3	14091.0	14137.6	14042.6	14445.2	14146.6
%			-2.66	-5.68	-3.28	-2.96	-3.61	-0.84	-2.89
Total (3-9)		4568.8	4679.2	4594.0	4614.1	4737.5	4571.9	4736.9	4737.4
%			2.41	0.55	0.99	3.69	0.07	3.68	3.69
Total (8-15)		**10343.6**	**9783.8**	**9336.9**	**9727.8**	**9748.7**	**9696.2**	**9993.1**	**9559.5**
%			**-5.41**	**-9.73**	**-5.95**	**-5.75**	**-6.26**	**-3.39**	**-7.58**

*: The duration of each time Interval is 3 minutes. **: No control situation.

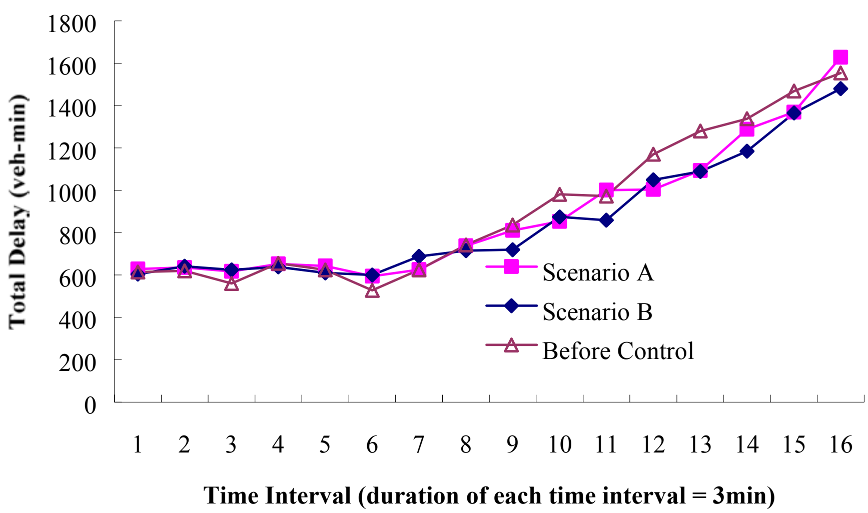

Figure 6.10 - Total Delay Over Time (Scenarios A and B)

From Tables 6.7 and 6.13, it was found that Scenario C was less efficient in increasing total throughput than that of Scenarios D, E and G for time intervals 3 to 9. It indicated that increasing metering rates at all metered ramps would not increase the total throughput. Scenarios E, F and G showed that decreasing metering rates at some upstream ramps (node 307 or 306) might be providing room to increase the metering rates at down stream ramps.

Summary

The dynamic system ramp metering control model with SPSA algorithm was developed to optimize ramp metering rates over time for single and multiple ramp metering control. The total throughput was the objective function. The real-time control algorithm with SPSA was set up and applied in the simulation models. The algorithm was effective in its application.

Simulation results showed that the benefits, such as increased total throughput and reduced total delay, could be obtained after the application of metering control. Multiple ramp control would be more effective than single ramp metering control in the system. The traffic performance of eastbound I-80 could be improved after metering control at some traffic situations suggested in Table 6.5 on page 85.

CONCLUSIONS AND RECOMMENDATIONS

In this study, the ramp metering control was proven to be a viable way to manage traffic operations on freeways, which could eliminate, or at least reduce, congestion on eastbound I-80. The potential benefit of ramp metering control and the development of a dynamic multi-ramp control model were discussed in detail. The constraints (e.g., meter locations, ramp storage capacities, lower and upper bounds of ramp metering rates) were formulated based on geometric and traffic conditions. Due to the absence of metering control at the study site, CORSIM was selected to simulate traffic operations under various metering control conditions. The SPSA algorithm was developed and applied to optimize the dynamic metering control model by maximizing the total throughput. The total throughput and the total delay of the study site under time-varying traffic conditions and different control strategies were thoroughly analyzed. Conclusions and recommendations are summarized next.

Conclusions

The findings of this study are discussed as follows:

- Short ramps do not only refer to those ramps short of physical storage area, but also depend on the ratio of the entering volume and the metering rate, which would affect the performance of ramp metering control. The feasible metering rates on the short ramps were between 240 vph and 900vph. Subject to the ramp storage constraint, the suggested lower bounds of metering rates on all potential ramps might be higher than 240 vph and are shown in Table 5.3 on page 53. For example, the lower bounds of metering rates at nodes 306, 307, 356, 376, and 395 were 370, 513, 860, 416 and 448 vph, respectively. If the ramp storage increased, the feasible range of metering rate and the benefit of metering control could be increased.
- A CORSIM model was calibrated and extensively applied in this study to evaluate freeway traffic operations under various ramp metering control strategies. A number of factors (e.g., traffic volumes, geometric conditions, and ramp metering rates)

affecting ramp metering control were analyzed. Various simulated MOEs (e.g., total throughput and delay, etc.) were generated for assessing the impact of proposed metering control on the study site.

- Unrestrained merging traffic on eastbound I-80 frequently resulted in bottlenecks during peak hours. When the sum of mainline volume and entry ramp volume exceeded mainline capacity, congestion and queue were formed. Thus, the freeway capacity decreased and the delay increased.

- The potential metered ramps connecting eastbound I-80 and Howard Boulevard South (with node 306), Howard Boulevard North (with node 307), Mount Hope Avenue (with node 356), Hibernia Avenue (with node 376), and E Main Street (with node 395) suitable for metering control of the study site were identified. The ramps on eastbound I-80 connecting Route 15 (MP 34.6) and Hibernia Avenue (MP 37.9) were not suggested to apply metering control.

- Simulation results indicated that for metering control at a single ramp, the performance of pre-timed control at node 395 outperformed that at other nodes. The total delay could be reduced by 5.09%. For demand/capacity metering situation, the control at node 376 outperformed that at other nodes. The total delay could be reduced by 4.29%.

- Under existing traffic demand, the reduced total delay or the increased total throughput was observed after metering control. However, the optimal metering control could not simultaneously minimize the total delay and maximize the total throughput.

- Ramp metering could provide a higher and more predictable level of service on the freeway. It also improved the efficiency of freeway operation by smoothing flow on the freeway.

- A dynamic multi-ramp metering control model was developed, which could capture dynamic traffic flow contraction over time and space. The developed SPSA solution algorithm could jointly optimize metering rates for multiple ramps in real-time by maximizing the total throughput.

- The developed dynamic multi-ramp metering control model was applied to single and multiple ramps while considering the peak demand of 4160 vph on the mainline. While optimizing single ramp control, simulation results showed that the maximum total throughput could be increased by 8.14% (control at node 306 in Table 6.3). While optimizing multiple ramp control, the total throughput was increased by 9.05% (Table 6.13). The developed multi-ramp control model was suitable to implement at the study site under peak demand condition.

- Considering time-varying traffic condition (Table 6.1) under single ramp control situation, simulation results showed that the total throughput and delay could be increased by 6.63% and reduced by 9.58% (Tables 6.3 and 6.4), respectively. While under multi-ramp control situation, the total throughput was increased by 8.07% (Table 6.13), and a considerable reduction of 9.73 % in total delay was achieved (Table 6.14). Therefore, the multi-ramp control outperformed the single ramp control in maximizing the total throughput at the study site.

- The dynamic multi-ramp metering control model was more efficient to increase total throughput when the range of mainline traffic entry flow is from 3360 vph to 4560 vph (Table 6.13), and was more efficient to reduce total delay when the entering volume of the mainline was from 4360 vph to 5760 vph (Table 6.14).

- In developing the dynamic multi-ramp metering control model, the large-scale non-linear relationship among control parameters increased the level of difficulty in optimizing the ramp metering control problem. The developed simultaneous perturbation stochastic approximation (SPSA) algorithm demonstrated significant advantages in solving the multivariate optimization problem formulated in this study.

Recommendations

- The potential ramps connecting Howard Boulevard (with node 306), Howard Boulevard (with node 307), Mount Hope Avenue (with node 356), Hibernia Avenue (with node 376) and East Main Street (with node 395) were recommended to apply ramp metering control.

- The developed dynamic multi-ramp metering control model was suggested to simultaneously control multiple ramps of the study site, which would ultimately improve traffic operations on I-80.

- In this study, the use of ramp metering control to maximize the total throughput worked well only within some traffic situations (e.g., the mainline entry flow within 3360 vph and 4560 vph), as shown in Table 6.5. Therefore, the traffic conditions such as mainline entry flow and traffic demand on ramps should be accurately detected, and then the decision of metering control could be made.

- In this study, the optimal metering rates were determined based on the data collected from simulation results of the previous time interval. The real-time and predicted traffic data could be applied to the developed model for advancing the developed ramp metering control model.

Future Study

- In this study, the constraint of ramp storage capacity was imposed that the queuing vehicles on ramps would not spillback onto local streets, and no vehicle diversions was assumed. In practice, vehicle diversion will occur when the freeway becomes congested and should be considered in the future.

- The traffic on arterials (e.g., NJ State Routes 10 and 46) near the study site and the signalized intersection control might affect the traffic flow on the freeway. It is essential that the study should be extended to cover the whole I-80 corridor.

Therefore, the impacts of ramp metering control, which will benefit travelers on both the freeway and arterials, can be better assessed.

- The application of advance control strategies, such as system-wide control and integrated system control, should be investigated and evaluated to seek more potential benefits (e.g. increasing throughput and speed, and reducing travel time, delay and emissions, etc.).

- While applying the dynamic multi-ramp metering control with SPSA, the traffic demand including O/D flow was fixed. With the application of ITS, traffic volumes can be detected in real-time, which provides a reliable input of actual traffic variations over time. Technologies in predicting traffic volume and delay should be developed.

- The developed model is a system-wide dynamic multi-ramp metering control model that can be used to handle a series of ramps in a traffic responsive schema. In order to process collected real-time traffic data, optimize metering rates, and execute the control mechanism through ramp meters in real-time, the optimization of ramp metering rates is often carried by centralized or decentralized computer systems. However, the system-wide models often lead to hierarchical non-linear optimization programming. The effectiveness of the centralized control versus the decentralized control should be evaluated in the future.

- In the dynamic multi-ramp metering control with SPSA, the objective function was to maximize the total throughput. Other objective functions, such as minimizing the total delay, minimizing emissions and fuel consumption, and improving local congestion can be considered with minor modification in the developed SPSA.

- The analysis of simulation results showed that achieving the maximum total throughput did not always achieve the minimum total delay. The tradeoff between the reduced delay and increased throughput should be considered in the future.

- The M/M/1 queuing model applied in this study assumed exponential vehicle arrivals and departures with one server. However, vehicles on ramps will more likely be discharged into the mainline deterministically under metering control. Thus, the M/D/1 model (exponentially distributed arrivals and deterministic departures with one server) applied into the developed dynamic metering control model should be studied.

- Closure of an entrance ramp represents the most restrictive form of metering but is the least popular because of considerable public opposition. Closure may mitigate serious weaving problems. In this study, ramp closure is not considered as a control strategy. However, it should be analyzed while traffic diversion on local streets is considered.

APPENDIX: CORSIM INPUT FILES

Because CORSIM simulates the time-varying traffic conditions of a network, the input must accommodate specifications that not only differ from one point on the network to another, but that might also change with time. Furthermore, the structure of the input stream must reflect the concept of network partitioning.

The time-varying portion of the simulation analysis is expressed as a sequence of “time periods” specified by the user; that is, the input data specified by the user for a certain time period remains in force unless changed in a subsequent time period. The user can specify up to 19 time periods and must specify the conditions that have changed during each period. Therefore, the input stream consists of a sequence of “blocks” of data records, with each block defining the conditions that apply to one time period.

For the CORSIM model, the spatial extent of the traffic environment is defined as a set of “sub-networks,” which reflect the concept of network partitioning. Each block of data records for a time period is subdivided into “sections” of data records. Some sections define conditions on particular sub-networks, while others provide inputs for the specifications that must be specified for the “global” network (such as bus routes).

Within each section, the input stream consists of a sequence of “record types,” which are also called “cards” and “card types.” Each record type contains a specific set of data items as well as an identification number.

On the following pages are examples of CORSIM input files. Example 1 is for no ramp metering control, and example 2 is for multiple ramps metering control.

EXAMPLE 1: NO RAMP METERING CONTROL CORSIM MODEL

```
          EVALUATION OF THE POTENTIAL FOR USING RAMP METERING                 00
                IN THE ATMS OF THE I-80 SHOWCASE CORRIDOR                     00
                                                                              00
                                  SPONSOR                                     00
                 NEW JERSEY DEPARTMENT OF TRANSPORTATION                      00
                                                                              00
A Sample Comment for No Ramp Metering Control CORSIM Model                    00
This data set introduces basic features of CORSIM and provides                00
the comment of coding for the study site.  This data set reflect              00
the real world case of I-80                                                   00
                                                                              00
8300--300--301------------302---303--340-----------341--351----------352--    00
             \            /     /      \           /      \          /        00
             350        306   307      346       345      355      356        00
                \       /     /          \       /          \      /          00
               8305   206   207         8346   245         8355  256          00
                      /     /                  /                 /            00
                    8306  8307               8345              8356           00
                                                                              00
                                                                              00
--371------------372---373--381-----------391--351--411--8411                 00
    \            /     /      \           /      \                            00
    375        376   377      385       395      355                          00
      \       /     /           \       /          \                          00
     8375   276   277          8385   295         8355                        00
            /     /                  /                                        00
          8376  8377               8395                                       00
                                                                              00
```

Record Type 00 must be the first record types. These records are comment cards that include alphanumeric information that the user wants to print on the first page of the output report. To insert comment cards in the data set, use blank record types (i.e., Columns 78-80 are blanks).

Record Types 01 through 05 are called control records. These five records are required for each data set and entered only in the first time period.

```
Ramp Metering                         03  25  01 Inst. of Trans., NJIT         1
by Noreen Zayas, Yuqing Ding, Jiangtao Luo and Xiaobo Liu
```

Record type 01 is the run identification card. It is used to indicate the use propose (e.g. Ramp Metering), date of run (3/25/01), name of the agency (e.g.Inst. of Trans., NJIT). Notice that 4 columns (45-48) are allocated for the year representation.

```
       1   0      60     7981   10  0        0 0   8 000        7781    0721   2
```

Record type 02 is the run control card. The '1' in column 8 indicates that a simulation run will be performed. The '0' in column 12 indicates that off-line incident detection, point processing and MOE estimation are not desired in this run. '60' is the maximum number of minutes of fill time prior to simulation. Simulation starts whether equilibrium is attained or not at the end of 60 minutes. Columns 22-29 (the '7981' in columns 26-29 ending with 1 is used to generate vehicle entry headway. The '10' in columns indicates fuel and emissions option for FRISIM. The '8' in column 52 specifies the model whose data appears after record type 02. The '8' denotes that the model is FRESIM. The '000' in columns 54-56 denotes the clock time (in military time) at the beginning of the simulation. Columns 61-68 ('7781), and 69-76 ('0721') provide the values for random number seeds.

```
 180 180 180 180 180 180 180 180 180 180 180 180 180 180 180 180                3
```

Record type 03 gives the time period specifications. The '180' indicates the duration of the each time period. In this run there is 16 time period.

```
           180                                                                  4
```

Record type 04 indicates the duration of the time step and the time interval per time period. The '60' is the duration of the time interval. The time step duration is specified in columns 12 to 16. Since in this run it is blank, the default value of 1 second is used. Notice that when both the NETSIM and FRESIM models are used this entry must be left blank. The '180' in columns 17-20 indicates the time interval duration of 180 seconds (3 minutes). Time interval duration controls the frequency by which cumulative simulation statistical results can be obtained.

```
                                                 9                              5
```

Record type 05 is the reports and graphics card. This card can be used to generate cumulative output and intermediate output.

In this test case, the FRESIM sub-network is coded first. Although the order in which sub-networks are input does not affect the simulation run, all of the records for a sub-network must be input in numerical order.

```
MP30-34 Mainline
8300 300 301     0 3                         1                                19
 300 301 302 58080 3 92  400                 1 9                              19
 301 302 303 13200 3                         1                                19
 302 303 340 10560 3 91  400                 1                                19
 303 340 341149420 3 91  400 92  400         1 9                              19
MP34-42
 340 341 351 53700 3                         1                                19
 341 351 352 29300 3 91 1000101  800 92  400 1 9                              19
 351 352 371 14700 4                         1                                19
 352 371 372102000 4 91  510 92  510         1 9                              19
 371 372 373 10500 4                         1                                19
 372 373 381 11000 4 91  640                 1                                19
 373 381 391 57700 4 91  650 92  650         1 9                              19
 381 391 411 43260 4                         1                                19
 391 4118411 62800 4 91  935                 1                                19
MP30-34 Ramps
 301 3058305  8451 1                         1                                19
8306 206 306     1 1                         1                                19
 206 306 302  7291 1                         1                                19
 306 302 303  4001 1                         9                                19
8307 207 307     1 1                         1                                19
 207 307 303  3871 1                         1                                19
 307 303 340  4001 1                         9                                19
 340 3468346 11921 1                         1                                19
```

```
MP34-42
8345 245 345     1 2                          1                                19
 245 345 341 12501 2                          1                                19
 345 341 351  4001 2                         10                                19
 351 3558355  6001 1                          1                                19
8356 256 356     1 1                          1                                19
 256 356 352  3001 1                          1                                19
 356 352 371  4001 1                          9                                19
 371 3758375  8291 1                          1                                19
8376 276 376     1 1                          1                                19
 276 376 372  4751 1                          1                                19
 376 372 373  3301 1                          9                                19
8377 277 377     1 1                          1                                19
 277 377 373  5501 1                          1                                19
 377 373 381  3201 1                          9                                19
 381 3858385  6531 1                          1                                19
8395 295 395     1 1                          1                                19
 295 395 391  4551 1                          1                                19
 395 391 411   401 1                          9                                19
```

Record type 19 is the link description card for the FRESIM model. One record type is required for each link. The entry and exit nodes are denoted by numbers between 8000 and 8999 (both inclusive). The upstream node number of the subject link is specified in columns 1-4 and the downstream node number is given in columns 5-8. The node that receives through traffic from the subject link is given in columns 9-12. Link lengths are indicated in columns 13-17. Link lengths are not specified for entry links. Column 20 indicates the number of through lanes in the link. Column 22 is the identification code for the first auxiliary lane. A '9' in that column represents the first auxiliary right lane. Column 23 indicates the lane type code for the specified auxiliary lane. A '1' specifies an acceleration lane, '2' specifies a deceleration lane, and a '3' specifies a full length auxiliary lane. Columns 24-28 indicate the length of the auxiliary lane. If another auxiliary lane exists, then the information is given in columns 29-44. Columns 45-46 denote the lane on the immediate downstream link that receives through traffic from lane 1 of the subject link represented in columns 1-8. Columns 47-48 denote the lane of the subject link that feeds lane 1 of the downstream off-ramp, if one exists. If there is no off-ramp it should be left blank.

```
MP30-34 Mainline
8300 300            65                                                         20
 300 301 1  5000    65       5800                                              20
 301 302            65                                                         20
 302 303            65                                                         20
 303 340    7500    65      14902                                              20

MP34-42 Mainline
 340 341    7500    65                                                         20
 341 351            65       2920                                              20
 351 352 2          65                                                         20
 352 371 1          65       5280                                              20
 371 372-2  2000    65                                                         20
 372 373    2000    65                                                         20
 373 381    6000    65       5750                                              20
 381 391    3500    65                                                         20
 391 411-2  5000    65                                                         20
MP30-34 Ramp
```

```
 301 305     500    25                                                        20
8306 206     600    25                                                        20
 206 306     600    25                                                        20
 306 302     600    25                                                        20
8307 207            25                                                        20
 207 307    2500    25                                                        20
 307 303    2500    25                                                        20
 340 346     500    25                                                        20
MP34-42 Ramp
8345 245    1100    30                                                        20
 245 345    1100    40                                                        20
 345 341    1100    30                                                        20
 351 355    1100    30                                                        20
8356 256            30                                                        20
 256 356            30                                                        20
 356 352            30                                                        20
 371 375            20                                                        20
8376 276     350    20                                                        20
 276 376     350    20                                                        20
 376 372     350    20                                                        20
8377 277     500    20                                                        20
 277 377     500    20                                                        20
 377 373     500    20                                                        20
 381 385     350    20                                                        20
8395 295            25                                                        20
 295 395            25                                                        20
 395 391            25                                                        20
```

Record Type 20 represents freeway link operations. A Record Type 20 is required for each link specified with a Record Type 19. Columns 1-4 include the link's upstream node number, and Columns 5-8 include the downstream node number. Columns 9-10, 11-12, and 13-16 specify the link's grade, super elevation, and radius of curvature, respectively. In this run, those columns were left blank, which indicates that default values are acceptable. Columns 21-22 show the desired free-flow speed (in miles per hour), which ranges from 20 to 65 mph in this run. Some of the links have an entry in Columns 29-33, which represents the distance (in feet) to the point at which drivers begin to react to the off-ramp exiting from this link. In FRESIM, this point is referred to as a warning sign. However, it does not mean the location of a physical sign. There is no entry if the link in question does not have an off-ramp destination.

```
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
```

```
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
```

Record Type 25 specifies freeway turn movements. Columns 1-4 include the link's upstream node number, and columns 5-8 include the downstream node number. Columns 9-12 show the downstream node number that receives through traffic from the subject link. Columns 13-16 show the percentage of vehicles that make the through movement. For this example, 94% of the vehicles on freeway link (300,301) are going through. The remainder (6%) will exit to node 305, which leads to an off-ramp.

```
 341 351   1 1    800                                                         32
```

Record Type 32 specifies the adding and/or dropping of freeway lanes. They must be specified wherever a through lane is added or dropped. Columns 1-4 include the link's upstream node number, and columns 5-8 include the downstream node number. A '1' in column 12 indicates a lane add (a '2' indicates a lane drop). The entry in column 14 is the identification number for the lane being added or dropped. Columns 17-21 specify the distance from the upstream node to the end of the lane drop or the beginning of the lane add. For link (341,351), lane 1 is being added, 800 feet from node 341.

Time Period 1

```
MP30-34
8300 3002960   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50
```

Record Type 50 describes the traffic volume (in vehicles per hour) entering the FRESIM network. Columns 1-4 include the upstream node number, and columns 5-8 include the downstream node number. Columns 9-12 show the volume. The number in columns 13-16 specifies the percentage of trucks entering from the entry node.

```
 130 120 110 100  90  80  70  60  50  40                                             68
```

Record Type 68 describes car-following sensitivity factor. The car-following model in FRESIM (the Pitt Car-Following Model) is based on the premise that drivers' desire to follow the car in front of them at a desired separation. In this example, there are 10 sensitivity factors from 130 to 40 (in hundredth of a second)for 10 driver types (Types 1 through 10). For instance, in this example, Columns 1-4 ('130') indicate that the new factor value is 130 hundredths of a second of ZFOLK(1) for driver type 1, while the '120' in Columns 5-8 indicate 120 hundredths of a second of ZFOLK(2) for driver type 2.

```
  30  12   2  60                                                                     70
```

Record Type 70 describes lane change parameters, minimum separation for vehicle generation, and maximum non-emergency deceleration for FRESIM. The '30' in Columns 1-4 indicates the time (30 tenths of a second)to complete a lane change. The '12' in Columns 5-8 indicates the minimum separation (12 tenths of a second)for generation of vehicles. The '2' in Column 12 indicates that drivers need 2 seconds for collision avoidance. The '60' in Columns indicates that there are 60% of drivers desiring to yield the right-of-way to lane-changing vehicles attempting to merge ahead of them.

```
MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
```

Record Type 74s represent origin-destination. Columns 1-4 and 5-8 include the link's upstream and the downstream node number, respectively. All of these columns are described as follows:

```
Entry 1:
        Column   1-4: origin node number
Entry 2:
        Column   5-8: destination node number
Entry 3:
        Column 11-12: percentage of vehicles that are
                      entering through the origin node
                      specified in Entry 1 and will travel
                      to the destination node specified in
                      Entry 2.
Entry 4-6:
        Column 13-24: Same as Entry 1-3 but for another
                      O/D exchange
Entry 7-9:
```

```
         Column 25-36: Same as Entry 1-3 but for another
                       O/D exchange
Entry 10-12:
         Column 37-38: Same as Entry 1-3 but for another
                       O/D exchange
Entry 13-15:
         Column 49-60: Same as Entry 1-3 but for another
                       O/D exchange
Entry 16-18:
         Column 61-72: Same as Entry 1-3 but for another
                       O/D exchange
```

```
                                                                             170
```

Record Type 170 is the sub-network delimiter. It indicates, in this case, the end of the FRESIM sub-network data.

```
   2   2   2                                                                 172
```

Record Type 172 represent environmental tables. The '2' in Columns 1-4 indicates that HC emission rate in the table is be modified. The '2' in Columns 5-8 indicates the vehicle performance index. The '2' in Columns 9-12 indicates the vehicle performance index 2 specified in Columns 5-8 had the same fuel or emission rate as another vehicle performance index.

```
MP30-42
8300                                                                        195
 300    9016    7692                                                        195
 301   13549    9031                                                        195
 302   14753    9131                                                        195
 303   15900    9231                                                        195
 340   21427   10011                                                        195
 341   25430    9747                                                        195
 351   28353   10065                                                        195
 352   29805   10373                                                        195
 371   39915   11605                                                        195
 372   40880   11340                                                        195
 373   41614   10725                                                        195
 381   43528    6083                                                        195
 391   45754    3107                                                        195
 411   50392     671                                                        195
8411                                                                        195
8305                                                                        195
 305   13905    8621                                                        195
8306   15173    8876                                                        195
 306   14572    8866                                                        195
 206   15050    8750                                                        195
8307                                                                        195
 207   15453    8804                                                        195
 307   15603    8974                                                        195
 346   21205    9230                                                        195
8346                                                                        195
8345                                                                        195
 245   24160    9255                                                        195
 345   25054    9680                                                        195
 355   28875    9851                                                        195
8355                                                                        195
8356                                                                        195
 256   29310    9878                                                        195
 356   29522   10090                                                        195
 375   40330   10887                                                        195
```

```
8375                                                                        195
8376                                                                        195
 276   40470   11048                                                        195
 376   40594   11294                                                        195
8377                                                                        195
 277   41042   10886                                                        195
 377   41391   10831                                                        195
 385   43172    5863                                                        195
8385                                                                        195
8395                                                                        195
 295   45259    3107                                                        195
 395   45714    3107                                                        195
```

Record type 195, defines the node coordinates. Columns 1-4 denote the intersection node number. Columns 7-12 refer to the X coordinate and columns 15-20 indicate the Y coordinate.

```
 300 301   2                                                                196
 303 340   1                                                                196
 340 341   2                                                                196
 371 372   1                                                                196
 372 373   1                                                                196
 373 381   1                                                                196
 381 391   2                                                                196
 391 411   1                                                                196
 301 305   2                                                                196
 306 302   1                                                                196
 206 306   1                                                                196
 307 303   1                                                                196
 207 307   1                                                                196
 340 346   1                                                                196
 345 341   1                                                                196
 245 345   1                                                                196
 351 355   1                                                                196
 376 372   1                                                                196
 276 376   1                                                                196
 377 373   1                                                                196
 277 377   1                                                                196
 381 385   1                                                                196
```

Record Type 196s specify the optional geometric data. These records are needed to graphically depict curved links and overpasses. Columns 1-4 and 5-8 define the upstream and downstream node numbers, respectively. Column 12 defines the link curvature in the direction of flow along that link. A '1' indicates a clockwise curvature; a '2' indicates counterclockwise curvature; and a '0' indicates no curvature.

```
   0   8                                                                    210
```

Record type 210 is the time period delimiter. The '0' in Columns 1-4 indicates that there is (are) other time period(s) follows. If '1' is in Columns 1-4, it indicates that this is the final time period and all simulation data have been entered. In the example, there are total 16 time periods.

```
MP30-34
8300 300 301 100                                                             25
 300 301 302  94 305   6                                                     25
 301 3058305 100                                                             25
```

```
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 2
MP30-34
8300 3003160   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
```

```
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 3
 306   1 360  55                                                              37
 307   1 360  47                                                              37
 345   1   0  97
 356   1 360  40                                                              37
 376   1 360  48                                                              37
 377   1   0  97
 395   1 360  45                                                              37
MP30-34
8300 3003326   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
```

```
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 4
MP30-34
8300 3003560   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
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 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
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   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 5
MP30-34
8300 3003760   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
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 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 6
MP30-34
8300 3003960   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
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 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 7
MP30-34
8300 3004160   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
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 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 8
MP30-34
8300 3004360   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
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 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69       74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                    74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                    74
 341 351   8 341 371   6 341 381   7 341 411  79                                74
 352 371   8 352 381   8 352 411  84                                            74
 372 381  12 372 411  88                                                        74
 373 381  12 373 411  88                                                        74
 391 411 100                                                                    74
                                                                               170
   0   8                                                                       210
MP30-34
8300 300 301 100                                                                25
 300 301 302  94 305   6                                                        25
 301 3058305 100                                                                25
 301 302 303 100                                                                25
8306 206 306 100                                                                25
 206 306 302 100                                                                25
 302 303 340 100                                                                25
8307 207 307 100                                                                25
 207 307 303 100                                                                25
 307 303 340 100                                                                25
 303 340 341  88 346  12                                                        25
 340 3468346 100                                                                25
MP34-42
 340 341 351 100                                                                25
 341 351 352  95 355   5                                                        25
 351 352 371 100                                                                25
 352 371 372  94 375   6                                                        25
 371 372 373 100                                                                25
 372 373 381 100                                                                25
 373 381 391  91 385   9                                                        25
 381 391 411 100                                                                25
 391 4118411 100                                                                25
8345 245 345 100                                                                25
 245 345 341 100                                                                25
 345 341 351 100                                                                25
 351 3558355 100                                                                25
8356 256 356 100                                                                25
 256 356 352 100                                                                25
 356 352 371 100                                                                25
 371 3758375 100                                                                25
8376 276 376 100                                                                25
 276 376 372 100                                                                25
 376 372 373 100                                                                25
8377 277 377 100                                                                25
 277 377 373 100                                                                25
 377 373 381 100                                                                25
 381 3858385 100                                                                25
8395 295 395 100                                                                25
 295 395 391 100                                                                25
 395 391 411 100                                                                25
Time Period 9
MP30-34
8300 3004560   6                                                                50
8306 206 360   4                                                                50
8307 207 489   8                                                                50
MP34-42
8345 2452159   9                                                                50
8356 256 819   8                                                                50
8376 276 400   5                                                                50
8377 2771216  10                                                                50
8395 295 430   9                                                                50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69       74
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 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                         74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                         74
 341 351   8 341 371   6 341 381   7 341 411  79                                     74
 352 371   8 352 381   8 352 411  84                                                 74
 372 381  12 372 411  88                                                             74
 373 381  12 373 411  88                                                             74
 391 411 100                                                                         74
                                                                                    170
   0   8                                                                            210
MP30-34
8300 300 301 100                                                                     25
 300 301 302  94 305   6                                                             25
 301 3058305 100                                                                     25
 301 302 303 100                                                                     25
8306 206 306 100                                                                     25
 206 306 302 100                                                                     25
 302 303 340 100                                                                     25
8307 207 307 100                                                                     25
 207 307 303 100                                                                     25
 307 303 340 100                                                                     25
 303 340 341  88 346  12                                                             25
 340 3468346 100                                                                     25
MP34-42
 340 341 351 100                                                                     25
 341 351 352  95 355   5                                                             25
 351 352 371 100                                                                     25
 352 371 372  94 375   6                                                             25
 371 372 373 100                                                                     25
 372 373 381 100                                                                     25
 373 381 391  91 385   9                                                             25
 381 391 411 100                                                                     25
 391 4118411 100                                                                     25
8345 245 345 100                                                                     25
 245 345 341 100                                                                     25
 345 341 351 100                                                                     25
 351 3558355 100                                                                     25
8356 256 356 100                                                                     25
 256 356 352 100                                                                     25
 356 352 371 100                                                                     25
 371 3758375 100                                                                     25
8376 276 376 100                                                                     25
 276 376 372 100                                                                     25
 376 372 373 100                                                                     25
8377 277 377 100                                                                     25
 277 377 373 100                                                                     25
 377 373 381 100                                                                     25
 381 3858385 100                                                                     25
8395 295 395 100                                                                     25
 295 395 391 100                                                                     25
 395 391 411 100                                                                     25
Time Period 10
MP30-34
8300 3004760   6                                                                     50
8306 206 360   4                                                                     50
8307 207 489   8                                                                     50
MP34-42
8345 2452159   9                                                                     50
8356 256 819   8                                                                     50
8376 276 400   5                                                                     50
8377 2771216  10                                                                     50
8395 295 430   9                                                                     50
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MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 11
MP30-34
8300 3004960   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
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8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 12
MP30-34
8300 3005160   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
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8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 13
MP30-34
8300 3005360   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
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8376 276 400   5                                                                 50
8377 2771216  10                                                                 50
8395 295 430   9                                                                 50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69       74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                   74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                   74
 341 351   8 341 371   6 341 381   7 341 411  79                               74
 352 371   8 352 381   8 352 411  84                                           74
 372 381  12 372 411  88                                                       74
 373 381  12 373 411  88                                                       74
 391 411 100                                                                   74
                                                                              170
   0   8                                                                      210
MP30-34
8300 300 301 100                                                               25
 300 301 302  94 305   6                                                       25
 301 3058305 100                                                               25
 301 302 303 100                                                               25
8306 206 306 100                                                               25
 206 306 302 100                                                               25
 302 303 340 100                                                               25
8307 207 307 100                                                               25
 207 307 303 100                                                               25
 307 303 340 100                                                               25
 303 340 341  88 346  12                                                       25
 340 3468346 100                                                               25
MP34-42
 340 341 351 100                                                               25
 341 351 352  95 355   5                                                       25
 351 352 371 100                                                               25
 352 371 372  94 375   6                                                       25
 371 372 373 100                                                               25
 372 373 381 100                                                               25
 373 381 391  91 385   9                                                       25
 381 391 411 100                                                               25
 391 4118411 100                                                               25
8345 245 345 100                                                               25
 245 345 341 100                                                               25
 345 341 351 100                                                               25
 351 3558355 100                                                               25
8356 256 356 100                                                               25
 256 356 352 100                                                               25
 356 352 371 100                                                               25
 371 3758375 100                                                               25
8376 276 376 100                                                               25
 276 376 372 100                                                               25
 376 372 373 100                                                               25
8377 277 377 100                                                               25
 277 377 373 100                                                               25
 377 373 381 100                                                               25
 381 3858385 100                                                               25
8395 295 395 100                                                               25
 295 395 391 100                                                               25
 395 391 411 100                                                               25
Time Period 14
MP30-34
8300 3005560   6                                                               50
8306 206 360   4                                                               50
8307 207 489   8                                                               50
MP34-42
8345 2452159   9                                                               50
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8356 256 819   8                                                             50
8376 276 400   5                                                             50
8377 2771216  10                                                             50
8395 295 430   9                                                             50

MP30-42 OD Table
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 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                 74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                 74
 341 351   8 341 371   6 341 381   7 341 411  79                             74
 352 371   8 352 381   8 352 411  84                                         74
 372 381  12 372 411  88                                                     74
 373 381  12 373 411  88                                                     74
 391 411 100                                                                 74
                                                                            170
   0   8                                                                    210
MP30-34
8300 300 301 100                                                             25
 300 301 302  94 305   6                                                     25
 301 3058305 100                                                             25
 301 302 303 100                                                             25
8306 206 306 100                                                             25
 206 306 302 100                                                             25
 302 303 340 100                                                             25
8307 207 307 100                                                             25
 207 307 303 100                                                             25
 307 303 340 100                                                             25
 303 340 341  88 346  12                                                     25
 340 3468346 100                                                             25
MP34-42
 340 341 351 100                                                             25
 341 351 352  95 355   5                                                     25
 351 352 371 100                                                             25
 352 371 372  94 375   6                                                     25
 371 372 373 100                                                             25
 372 373 381 100                                                             25
 373 381 391  91 385   9                                                     25
 381 391 411 100                                                             25
 391 4118411 100                                                             25
8345 245 345 100                                                             25
 245 345 341 100                                                             25
 345 341 351 100                                                             25
 351 3558355 100                                                             25
8356 256 356 100                                                             25
 256 356 352 100                                                             25
 356 352 371 100                                                             25
 371 3758375 100                                                             25
8376 276 376 100                                                             25
 276 376 372 100                                                             25
 376 372 373 100                                                             25
8377 277 377 100                                                             25
 277 377 373 100                                                             25
 377 373 381 100                                                             25
 381 3858385 100                                                             25
8395 295 395 100                                                             25
 295 395 391 100                                                             25
 395 391 411 100                                                             25
Time Period 15
MP30-34
8300 3005760   6                                                             50
8306 206 360   4                                                             50
8307 207 489   8                                                             50
MP34-42
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8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 16
MP30-34
8300 3005960   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
```

```
MP34-42
8345 2452159   9                                                                  50
8356 256 819   8                                                                  50
8376 276 400   5                                                                  50
8377 2771216  10                                                                  50
8395 295 430   9                                                                  50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69          74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                      74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                      74
 341 351   8 341 371   6 341 381   7 341 411  79                                  74
 352 371   8 352 381   8 352 411  84                                              74
 372 381  12 372 411  88                                                          74
 373 381  12 373 411  88                                                          74
 391 411 100                                                                      74
                                                                                 170
   1                                                                             210
```

EXAMPLE 2. MULTIPLE RAMPS METERING CONTROL CORSIM MODEL

```
          EVALUATION OF THE POTENTIAL FOR USING RAMP METERING                 00
                IN THE ATMS OF THE I-80 SHOWCASE CORRIDOR                     00
                                                                              00
                                  SPONSOR                                     00
                 NEW JERSEY DEPARTMENT OF TRANSPORTATION                      00
                                                                              00
A Sample Comment for Multiple Ramps Metering Control CORSIM Model             00
                                                                              00
This data set introduces basic features of CORSIM and provides                00
the comment of coding for the study site.  This data set reflect              00
the real world case of I-80                                                   00
                                                                              00
                                                                              00
8300--300--301------------302---303--340-----------341--351----------352--    00
            \             /     /      \            /     \           /       00
             350        306   307      346       345      355      356        00
                \       /     /          \       /          \      /          00
               8305   206   207         8346   245         8355  256          00
                      /     /                  /                 /            00
                    8306  8307               8345              8356           00
                                                                              00
                                                                              00
--371------------372---373--381-----------391--351--411--8411                 00
    \            /     /      \           /      \                            00
    375        376   377      385       395      355                          00
      \       /     /           \       /          \                          00
     8375   276   277          8385   295         8355                        00
            /     /                  /                                        00
          8376  8377               8395                                       00
                                                                              00
```

Record Type 00 must be the first record types. These records are comment cards that include alphanumeric information that the user wants to print on the first page of the output report. To insert comment cards in the data set, use blank record types (i.e., Columns 78-80 are blanks).

Record Types 01 through 05 are called control records. These five records are required for each data set and entered only in the first time period.

```
Ramp Metering                         03  25  01 Inst. of Trans., NJIT         1
by Noreen Zayas, Yuqing Ding, Jiangtao Luo and Xiaobo Liu
```

Record type 01 is the run identification card. It is used to indicate the use propose (e.g. Ramp Metering), date of run (3/25/01), name of the agency (e.g.Inst. of Trans., NJIT). Notice that 4 columns (45-48) are allocated for the year representation.

```
       1   0      60     7981   10  0        0 0   8 000        7781    0721   2
```

Record type 02 is the run control card. The '1' in column 8 indicates that a simulation run will be performed. The '0' in column 12 indicates that off-line incident detection, point processing and MOE estimation are not desired in this run. '60' is the maximum number of minutes of fill time prior to simulation. Simulation starts whether equilibrium is attained or not at the end of 60 minutes. Columns 22-29 (the '7981' in columns 26-29 ending with 1 is used to generate vehicle entry headway. The '10' in columns indicates fuel and emissions option for FRISIM. The '8' in column 52 specifies the model whose data appears after record type 02. The '8' denotes that the model is FRESIM. The '000' in columns 54-56 denotes the clock time (in military time) at the beginning of the simulation. Columns 61-68 ('7781), and 69-76 ('0721') provide the values for random number seeds.

```
 180 180 180 180 180 180 180 180 180 180 180 180 180 180 180 180                  3
```

Record type 03 gives the time period specifications. The '180' indicates the duration of the each time period. In this run there is 16 time period.

```
           180                                                                    4
```

Record type 04 indicates the duration of the time step and the time interval per time period. The '60' is the duration of the time interval. The time step duration is specified in columns 12 to 16. Since in this run it is blank, the default value of 1 second is used. Notice that when both the NETSIM and FRESIM models are used this entry must be left blank. The '180' in columns 17-20 indicates the time interval duration of 180 seconds (3 minutes). Time interval duration controls the frequency by which cumulative simulation statistical results can be obtained.

```
                                                9                                 5
```

Record type 05 is the reports and graphics card. This card can be used to generate cumulative output and intermediate output.

In this test case, the FRESIM sub-network is coded first. Although the order in which sub-networks are input does not affect the simulation run, all of the records for a sub-network must be input in numerical order.

```
MP30-34 Mainline
8300 300 301     0 3                      1                                      19
 300 301 302 58080 3 92  400              1 9                                    19
 301 302 303 13200 3                      1                                      19
 302 303 340 10560 3 91  400              1                                      19
 303 340 341149420 3 91  400 92  400      1 9                                    19
MP34-42
 340 341 351 53700 3                      1                                      19
 341 351 352 29300 3 91 1000101  800 92  400 1 9                                 19
 351 352 371 14700 4                      1                                      19
 352 371 372102000 4 91  510 92  510      1 9                                    19
 371 372 373 10500 4                      1                                      19
 372 373 381 11000 4 91  640              1                                      19
 373 381 391 57700 4 91  650 92  650      1 9                                    19
 381 391 411 43260 4                      1                                      19
 391 4118411 62800 4 91  935              1                                      19
MP30-34 Ramps
 301 3058305  8451 1                      1                                      19
8306 206 306     1 1                      1                                      19
 206 306 302  7291 1                      1                                      19
 306 302 303  4001 1                      9                                      19
8307 207 307     1 1                      1                                      19
 207 307 303  3871 1                      1                                      19
```

```
 307 303 340  4001 1                         9                                19
 340 3468346 11921 1                         1                                19
MP34-42
8345 245 345     1 2                         1                                19
 245 345 341 12501 2                         1                                19
 345 341 351  4001 2                        10                                19
 351 3558355  6001 1                         1                                19
8356 256 356     1 1                         1                                19
 256 356 352  3001 1                         1                                19
 356 352 371  4001 1                         9                                19
 371 3758375  8291 1                         1                                19
8376 276 376     1 1                         1                                19
 276 376 372  4751 1                         1                                19
 376 372 373  3301 1                         9                                19
8377 277 377     1 1                         1                                19
 277 377 373  5501 1                         1                                19
 377 373 381  3201 1                         9                                19
 381 3858385  6531 1                         1                                19
8395 295 395     1 1                         1                                19
 295 395 391  4551 1                         1                                19
 395 391 411   401 1                         9                                19
```

Record type 19 is the link description card for the FRESIM model. One record type is required for each link. The entry and exit nodes are denoted by numbers between 8000 and 8999 (both inclusive). The upstream node number of the subject link is specified in columns 1-4 and the downstream node number is given in columns 5-8. The node that receives through traffic from the subject link is given in columns 9-12. Link lengths are indicated in columns 13-17. Link lengths are not specified for entry links. Column 20 indicates the number of through lanes in the link. Column 22 is the identification code for the first auxiliary lane. A '9' in that column represents the first auxiliary right lane. Column 23 indicates the lane type code for the specified auxiliary lane. A '1' specifies an acceleration lane, '2' specifies a deceleration lane, and a '3' specifies a full length auxiliary lane. Columns 24-28 indicate the length of the auxiliary lane. If another auxiliary lane exists, then the information is given in columns 29-44. Columns 45-46 denote the lane on the immediate downstream link that receives through traffic from lane 1 of the subject link represented in columns 1-8. Columns 47-48 denote the lane of the subject link that feeds lane 1 of the downstream off-ramp, if one exists. If there is no off-ramp it should be left blank.

```
MP30-34 Mainline
8300 300            65                                                        20
 300 301 1  5000    65       5800                                             20
 301 302            65                                                        20
 302 303            65                                                        20
 303 340    7500    65      14902                                             20

MP34-42 Mainline
 340 341    7500    65                                                        20
 341 351            65       2920                                             20
 351 352 2          65                                                        20
 352 371 1          65       5280                                             20
 371 372-2  2000    65                                                        20
 372 373    2000    65                                                        20
 373 381    6000    65       5750                                             20
 381 391    3500    65                                                        20
```

```
 391 411-2  5000    65                                                        20
MP30-34 Ramp
 301 305     500    25                                                        20
8306 206     600    25                                                        20
 206 306     600    25                                                        20
 306 302     600    25                                                        20
8307 207            25                                                        20
 207 307    2500    25                                                        20
 307 303    2500    25                                                        20
 340 346     500    25                                                        20
MP34-42 Ramp
8345 245    1100    30                                                        20
 245 345    1100    40                                                        20
 345 341    1100    30                                                        20
 351 355    1100    30                                                        20
8356 256            30                                                        20
 256 356            30                                                        20
 356 352            30                                                        20
 371 375            20                                                        20
8376 276     350    20                                                        20
 276 376     350    20                                                        20
 376 372     350    20                                                        20
8377 277     500    20                                                        20
 277 377     500    20                                                        20
 377 373     500    20                                                        20
 381 385     350    20                                                        20
8395 295            25                                                        20
 295 395            25                                                        20
 395 391            25                                                        20
```

Record Type 20 represents freeway link operations. A Record Type 20 is required for each link specified with a Record Type 19. Columns 1-4 include the link's upstream node number, and Columns 5-8 include the downstream node number. Columns 9-10, 11-12, and 13-16 specify the link's grade, super elevation, and radius of curvature, respectively. In this run, those columns were left blank, which indicates that default values are acceptable. Columns 21-22 show the desired free-flow speed (in miles per hour), which ranges from 20 to 65 mph in this run. Some of the links have an entry in Columns 29-33, which represents the distance (in feet) to the point at which drivers begin to react to the off-ramp exiting from this link. In FRESIM, this point is referred to as a warning sign. However, it does not mean the location of a physical sign. There is no entry if the link in question does not have an off-ramp destination.

```
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
```

```
 341 351 352  95 355   5                                                           25
 351 352 371 100                                                                   25
 352 371 372  94 375   6                                                           25
 371 372 373 100                                                                   25
 372 373 381 100                                                                   25
 373 381 391  91 385   9                                                           25
 381 391 411 100                                                                   25
 391 4118411 100                                                                   25
8345 245 345 100                                                                   25
 245 345 341 100                                                                   25
 345 341 351 100                                                                   25
 351 3558355 100                                                                   25
8356 256 356 100                                                                   25
 256 356 352 100                                                                   25
 356 352 371 100                                                                   25
 371 3758375 100                                                                   25
8376 276 376 100                                                                   25
 276 376 372 100                                                                   25
 376 372 373 100                                                                   25
8377 277 377 100                                                                   25
 277 377 373 100                                                                   25
 377 373 381 100                                                                   25
 381 3858385 100                                                                   25
8395 295 395 100                                                                   25
 295 395 391 100                                                                   25
 395 391 411 100                                                                   25
```

Record Type 25 specifies freeway turn movements. Columns 1-4 include the link's upstream node number, and columns 5-8 include the downstream node number. Columns 9-12 show the downstream node number that receives through traffic from the subject link. Columns 13-16 show the percentage of vehicles that make the through movement. For this example, 94% of the vehicles on freeway link (300,301) are going through. The remainder (6%) will exit to node 305, which leads to an off-ramp.

```
 341 351   1 1    800                                                              32
```

Record Type 32 specifies the adding and/or dropping of freeway lanes. They must be specified wherever a through lane is added or dropped. Columns 1-4 include the link's upstream node number, and columns 5-8 include the downstream node number. A '1' in column 12 indicates a lane add (a '2' indicates a lane drop). The entry in column 14 is the identification number for the lane being added or dropped. Columns 17-21 specify the distance from the upstream node to the end of the lane drop or the beginning of the lane add. For link (341,351), lane 1 is being added, 800 feet from node 341.

```
Time Period 1
 306   1   0  55                                                                   37
 307   1   0  47                                                                   37
 345   1   0  97
 356   1   0  40                                                                   37
 376   1   0  48                                                                   37
 377   1   0  97
 395   1   0  45                                                                   37
```

Record Type 37 specifies freeway ramp metering control. One type of ramp metering control strategies is coded in this test case: pre-timed time (clock time).

The above line with node "306" in is an example of how to code the control card. The '306' indicates the node number at which the metering signal is located. The '1' in column 8 indicates a clock-time metering strategy. The '0' in columns 9-12 indicates the number of seconds from the onset of metering from the beginning of the simulation. The '55' in columns 15-16 indicates the metering headway (in tenths of a second) for clock-time metering.

```
MP30-34
8300 3002960   6                                                                    50
8306 206 360   4                                                                    50
8307 207 489   8                                                                    50
MP34-42
8345 2452159   9                                                                    50
8356 256 819   8                                                                    50
8376 276 400   5                                                                    50
8377 2771216  10                                                                    50
8395 295 430   9                                                                    50
```

Record Type 50 describes the traffic volume (in vehicles per hour) entering the FRESIM network. Columns 1-4 include the upstream node number, and columns 5-8 include the downstream node number. Columns 9-12 show the volume. The number in columns 13-16 specifies the percentage of trucks entering from the entry node.

```
 130 120 110 100  90  80  70  60  50  40                                           68
```

Record Type 68 describes car-following sensitivity factor. The car-following model in FRESIM (the Pitt Car-Following Model) is based on the premise that drivers' desire to follow the car in front of them at a desired separation. In this example, there are 10 sensitivity factors from 130 to 40 (in hundredth of a second)for 10 driver types (Types 1 through 10). For instance, in this example, Columns 1-4 ('130') indicate that the new factor value is 130 hundredths of a second of ZFOLK(1) for driver type 1, while the '120' in Columns 5-8 indicate 120 hundredths of a second of ZFOLK(2) for driver type 2.

```
  30  12   2  60                                                                    70
```

Record Type 70 describes lane change parameters, minimum separation for vehicle generation, and maximum non-emergency deceleration for FRESIM. The '30' in Columns 1-4 indicates the time (30 tenths of a second)to complete a lane change. The '12' in Columns 5-8 indicates the minimum separation (12 tenths of a second)for generation of vehicles. The '2' in Column 12 indicates that drivers need 2 seconds for collision avoidance. The '60' in Columns indicates that there are 60% of drivers desiring to yield the right-of-way to lane-changing vehicles attempting to merge ahead of them.

```
MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
```

```
 372 381  12 372 411  88                                                        74
 373 381  12 373 411  88                                                        74
 391 411 100                                                                    74
```

Record Type 74s represent origin-destination. Columns 1-4 and 5-8 include the link's upstream and the downstream node number, respectively. All of these columns are described as follows:

```
Entry 1:
        Column   1-4: origin node number
Entry 2:
        Column   5-8: destination node number
Entry 3:
        Column 11-12: percentage of vehicles that are
                      entering through the origin node
                      specified in Entry 1 and will travel
                      to the destination node specified in
                      Entry 2.
Entry 4-6:
        Column 13-24: Same as Entry 1-3 but for another
                      O/D exchange
Entry 7-9:
        Column 25-36: Same as Entry 1-3 but for another
                      O/D exchange
Entry 10-12:
        Column 37-38: Same as Entry 1-3 but for another
                      O/D exchange
Entry 13-15:
        Column 49-60: Same as Entry 1-3 but for another
                      O/D exchange
Entry 16-18:
        Column 61-72: Same as Entry 1-3 but for another
                      O/D exchange
```

```
                                                                               170
```

Record Type 170 is the sub-network delimiter. It indicates, in this case, the end of the FRESIM sub-network data.

```
   2   2   2                                                                   172
```

Record Type 172 represent environmental tables. The '2' in Columns 1-4 indicates that HC emission rate in the table is be modified. The '2' in Columns 5-8 indicates the vehicle performance index. The '2' in Columns 9-12 indicates the vehicle performance index 2 specified in Columns 5-8 had the same fuel or emission rate as another vehicle performance index.

```
MP30-42
8300                                                                           195
 300    9016    7692                                                           195
 301   13549    9031                                                           195
 302   14753    9131                                                           195
 303   15900    9231                                                           195
 340   21427   10011                                                           195
 341   25430    9747                                                           195
 351   28353   10065                                                           195
 352   29805   10373                                                           195
 371   39915   11605                                                           195
 372   40880   11340                                                           195
 373   41614   10725                                                           195
```

```
 381   43528    6083                                                            195
 391   45754    3107                                                            195
 411   50392     671                                                            195
8411                                                                            195
8305                                                                            195
 305   13905    8621                                                            195
8306   15173    8876                                                            195
 306   14572    8866                                                            195
 206   15050    8750                                                            195
8307                                                                            195
 207   15453    8804                                                            195
 307   15603    8974                                                            195
 346   21205    9230                                                            195
8346                                                                            195
8345                                                                            195
 245   24160    9255                                                            195
 345   25054    9680                                                            195
 355   28875    9851                                                            195
8355                                                                            195
8356                                                                            195
 256   29310    9878                                                            195
 356   29522   10090                                                            195
 375   40330   10887                                                            195
8375                                                                            195
8376                                                                            195
 276   40470   11048                                                            195
 376   40594   11294                                                            195
8377                                                                            195
 277   41042   10886                                                            195
 377   41391   10831                                                            195
 385   43172    5863                                                            195
8385                                                                            195
8395                                                                            195
 295   45259    3107                                                            195
 395   45714    3107                                                            195
```

Record type 195, defines the node coordinates. Columns 1-4 denote the intersection node number. Columns 7-12 refer to the X coordinate and columns 15-20 indicate the Y coordinate.

```
 300 301   2                                                                    196
 303 340   1                                                                    196
 340 341   2                                                                    196
 371 372   1                                                                    196
 372 373   1                                                                    196
 373 381   1                                                                    196
 381 391   2                                                                    196
 391 411   1                                                                    196
 301 305   2                                                                    196
 306 302   1                                                                    196
 206 306   1                                                                    196
 307 303   1                                                                    196
 207 307   1                                                                    196
 340 346   1                                                                    196
 345 341   1                                                                    196
 245 345   1                                                                    196
 351 355   1                                                                    196
 376 372   1                                                                    196
 276 376   1                                                                    196
 377 373   1                                                                    196
 277 377   1                                                                    196
 381 385   1                                                                    196
```

Record Type 196s specify the optional geometric data. These records are needed to graphically depict curved links and overpasses. Columns 1-4 and 5-8 define the upstream and downstream node numbers, respectively. Column 12 defines the link curvature in the direction of flow along that link. A '1' indicates a clockwise curvature; a '2' indicates counterclockwise curvature; and a '0' indicates no curvature.

```
   0   8                                                                    210
```

Record type 210 is the time period delimiter. The '0' in Columns 1-4 indicates that there is (are) other time period(s) follows. If '1' is in Columns 1-4, it indicates that this is the final time period and all simulation data have been entered. In the example, there are total 16 time periods.

```
MP30-34
8300 300 301 100                                                             25
 300 301 302  94 305   6                                                     25
 301 3058305 100                                                             25
 301 302 303 100                                                             25
8306 206 306 100                                                             25
 206 306 302 100                                                             25
 302 303 340 100                                                             25
8307 207 307 100                                                             25
 207 307 303 100                                                             25
 307 303 340 100                                                             25
 303 340 341  88 346  12                                                     25
 340 3468346 100                                                             25
MP34-42
 340 341 351 100                                                             25
 341 351 352  95 355   5                                                     25
 351 352 371 100                                                             25
 352 371 372  94 375   6                                                     25
 371 372 373 100                                                             25
 372 373 381 100                                                             25
 373 381 391  91 385   9                                                     25
 381 391 411 100                                                             25
 391 4118411 100                                                             25
8345 245 345 100                                                             25
 245 345 341 100                                                             25
 345 341 351 100                                                             25
 351 3558355 100                                                             25
8356 256 356 100                                                             25
 256 356 352 100                                                             25
 356 352 371 100                                                             25
 371 3758375 100                                                             25
8376 276 376 100                                                             25
 276 376 372 100                                                             25
 376 372 373 100                                                             25
8377 277 377 100                                                             25
 277 377 373 100                                                             25
 377 373 381 100                                                             25
 381 3858385 100                                                             25
8395 295 395 100                                                             25
 295 395 391 100                                                             25
 395 391 411 100                                                             25
Time Period 2
 306   1 180  55                                                             37
 307   1 180  47                                                             37
```

```
 345   1   0  97
 356   1 180  40                                                              37
 376   1 180  48                                                              37
 377   1   0  97
 395   1 180  45                                                              37
MP30-34
8300 3003160   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
```

```
 377 373 381 100                                                            25
 381 3858385 100                                                            25
8395 295 395 100                                                            25
 295 395 391 100                                                            25
 395 391 411 100                                                            25
Time Period 3
 306   1 360  55                                                            37
 307   1 360  47                                                            37
 345   1   0  97
 356   1 360  40                                                            37
 376   1 360  48                                                            37
 377   1   0  97
 395   1 360  45                                                            37
MP30-34
8300 3003326   6                                                            50
8306 206 360   4                                                            50
8307 207 489   8                                                            50
MP34-42
8345 2452159   9                                                            50
8356 256 819   8                                                            50
8376 276 400   5                                                            50
8377 2771216  10                                                            50
8395 295 430   9                                                            50

MP30-42 OD Table
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 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                   74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                   74
 341 351   8 341 371   6 341 381   7 341 411  79                               74
 352 371   8 352 381   8 352 411  84                                           74
 372 381  12 372 411  88                                                       74
 373 381  12 373 411  88                                                       74
 391 411 100                                                                   74
                                                                              170
   0   8                                                                      210
MP30-34
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 300 301 302  94 305   6                                                    25
 301 3058305 100                                                            25
 301 302 303 100                                                            25
8306 206 306 100                                                            25
 206 306 302 100                                                            25
 302 303 340 100                                                            25
8307 207 307 100                                                            25
 207 307 303 100                                                            25
 307 303 340 100                                                            25
 303 340 341  88 346  12                                                    25
 340 3468346 100                                                            25
MP34-42
 340 341 351 100                                                            25
 341 351 352  95 355   5                                                    25
 351 352 371 100                                                            25
 352 371 372  94 375   6                                                    25
 371 372 373 100                                                            25
 372 373 381 100                                                            25
 373 381 391  91 385   9                                                    25
 381 391 411 100                                                            25
 391 4118411 100                                                            25
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 245 345 341 100                                                            25
 345 341 351 100                                                            25
 351 3558355 100                                                            25
8356 256 356 100                                                            25
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 356 352 371 100                                                            25
 371 3758375 100                                                            25
8376 276 376 100                                                            25
 276 376 372 100                                                            25
 376 372 373 100                                                            25
8377 277 377 100                                                            25
 277 377 373 100                                                            25
 377 373 381 100                                                            25
 381 3858385 100                                                            25
8395 295 395 100                                                            25
 295 395 391 100                                                            25
 395 391 411 100                                                            25
Time Period 4
 306   1 540  54                                                            37
 307   1 540  47                                                            37
 345   1   0  97
 356   1 540  40                                                            37
 376   1 540  47                                                            37
 377   1   0  97
 395   1 540  44                                                            37
MP30-34
8300 3003560   6                                                            50
8306 206 360   4                                                            50
8307 207 489   8                                                            50
MP34-42
8345 2452159   9                                                            50
8356 256 819   8                                                            50
8376 276 400   5                                                            50
8377 2771216  10                                                            50
8395 295 430   9                                                            50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69       74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                   74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                   74
 341 351   8 341 371   6 341 381   7 341 411  79                               74
 352 371   8 352 381   8 352 411  84                                           74
 372 381  12 372 411  88                                                       74
 373 381  12 373 411  88                                                       74
 391 411 100                                                                   74
                                                                              170
   0   8                                                                      210
MP30-34
8300 300 301 100                                                            25
 300 301 302  94 305   6                                                    25
 301 3058305 100                                                            25
 301 302 303 100                                                            25
8306 206 306 100                                                            25
 206 306 302 100                                                            25
 302 303 340 100                                                            25
8307 207 307 100                                                            25
 207 307 303 100                                                            25
 307 303 340 100                                                            25
 303 340 341  88 346  12                                                    25
 340 3468346 100                                                            25
MP34-42
 340 341 351 100                                                            25
 341 351 352  95 355   5                                                    25
 351 352 371 100                                                            25
 352 371 372  94 375   6                                                    25
 371 372 373 100                                                            25
 372 373 381 100                                                            25
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 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 5
 306   1 720  53                                                              37
 307   1 720  47                                                              37
 345   1   0  97
 356   1 720  40                                                              37
 376   1 720  46                                                              37
 377   1   0  97
 395   1 720  43                                                              37
MP30-34
8300 3003760   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
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 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
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MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 6
 306   1 900  52                                                              37
 307   1 900  46                                                              37
 345   1   0  97
 356   1 900  40                                                              37
 376   1 900  45                                                              37
 377   1   0  97
 395   1 900  42                                                              37
MP30-34
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8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
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8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
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 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
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 206 306 302 100                                                                 25
 302 303 340 100                                                                 25
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 207 307 303 100                                                                 25
 307 303 340 100                                                                 25
 303 340 341  88 346  12                                                         25
 340 3468346 100                                                                 25
MP34-42
 340 341 351 100                                                                 25
 341 351 352  95 355   5                                                         25
 351 352 371 100                                                                 25
 352 371 372  94 375   6                                                         25
 371 372 373 100                                                                 25
 372 373 381 100                                                                 25
 373 381 391  91 385   9                                                         25
 381 391 411 100                                                                 25
 391 4118411 100                                                                 25
8345 245 345 100                                                                 25
 245 345 341 100                                                                 25
 345 341 351 100                                                                 25
 351 3558355 100                                                                 25
8356 256 356 100                                                                 25
 256 356 352 100                                                                 25
 356 352 371 100                                                                 25
 371 3758375 100                                                                 25
8376 276 376 100                                                                 25
 276 376 372 100                                                                 25
 376 372 373 100                                                                 25
8377 277 377 100                                                                 25
 277 377 373 100                                                                 25
 377 373 381 100                                                                 25
 381 3858385 100                                                                 25
8395 295 395 100                                                                 25
 295 395 391 100                                                                 25
 395 391 411 100                                                                 25
Time Period 7
 306   11080  51                                                                 37
 307   11080  45                                                                 37
 345   1   0  97
 356   11080  40                                                                 37
 376   11080  44                                                                 37
 377   1   0  97
 395   11080  41                                                                 37
MP30-34
8300 3004160   6                                                                 50
8306 206 360   4                                                                 50
8307 207 489   8                                                                 50
MP34-42
8345 2452159   9                                                                 50
8356 256 819   8                                                                 50
8376 276 400   5                                                                 50
8377 2771216  10                                                                 50
8395 295 430   9                                                                 50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69         74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                     74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                     74
 341 351   8 341 371   6 341 381   7 341 411  79                                 74
 352 371   8 352 381   8 352 411  84                                             74
 372 381  12 372 411  88                                                         74
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 373 381  12 373 411  88                        74
 391 411 100                                    74
                                               170
   0   8                                       210
MP30-34
8300 300 301 100                                25
 300 301 302  94 305   6                        25
 301 3058305 100                                25
 301 302 303 100                                25
8306 206 306 100                                25
 206 306 302 100                                25
 302 303 340 100                                25
8307 207 307 100                                25
 207 307 303 100                                25
 307 303 340 100                                25
 303 340 341  88 346  12                        25
 340 3468346 100                                25
MP34-42
 340 341 351 100                                25
 341 351 352  95 355   5                        25
 351 352 371 100                                25
 352 371 372  94 375   6                        25
 371 372 373 100                                25
 372 373 381 100                                25
 373 381 391  91 385   9                        25
 381 391 411 100                                25
 391 4118411 100                                25
8345 245 345 100                                25
 245 345 341 100                                25
 345 341 351 100                                25
 351 3558355 100                                25
8356 256 356 100                                25
 256 356 352 100                                25
 356 352 371 100                                25
 371 3758375 100                                25
8376 276 376 100                                25
 276 376 372 100                                25
 376 372 373 100                                25
8377 277 377 100                                25
 277 377 373 100                                25
 377 373 381 100                                25
 381 3858385 100                                25
8395 295 395 100                                25
 295 395 391 100                                25
 395 391 411 100                                25
Time Period 8
 306   11260  50                                37
 307   11260  45                                37
 345   1   0  97
 356   11260  40                                37
 376   11260  44                                37
 377   1   0  97
 395   11260  41                                37
MP30-34
8300 3004360   6                                50
8306 206 360   4                                50
8307 207 489   8                                50
MP34-42
8345 2452159   9                                50
8356 256 819   8                                50
8376 276 400   5                                50
8377 2771216  10                                50
8395 295 430   9                                50
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MP30-42 OD Table
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 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 9
 306   11440  50                                                              37
 307   11440  45                                                              37
 345   1   0  97
 356   11440  40                                                              37
 376   11440  44                                                              37
 377   1   0  97
 395   11440  41                                                              37
MP30-34
8300 3004560   6                                                              50
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8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
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8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 10
 306   11620  50                                                              37
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 307   11620  48                                                                                 37
 345   1   0  97
 356   11620  40                                                                                 37
 376   11620  40                                                                                 37
 377   1   0  97
 395   11620  40                                                                                 37
MP30-34
8300 3004760   6                                                                                 50
8306 206 360   4                                                                                 50
8307 207 489   8                                                                                 50
MP34-42
8345 2452159   9                                                                                 50
8356 256 819   8                                                                                 50
8376 276 400   5                                                                                 50
8377 2771216  10                                                                                 50
8395 295 430   9                                                                                 50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69                         74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                                     74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                                     74
 341 351   8 341 371   6 341 381   7 341 411  79                                                 74
 352 371   8 352 381   8 352 411  84                                                             74
 372 381  12 372 411  88                                                                         74
 373 381  12 373 411  88                                                                         74
 391 411 100                                                                                     74
                                                                                                170
   0   8                                                                                        210
MP30-34
8300 300 301 100                                                                                 25
 300 301 302  94 305   6                                                                         25
 301 3058305 100                                                                                 25
 301 302 303 100                                                                                 25
8306 206 306 100                                                                                 25
 206 306 302 100                                                                                 25
 302 303 340 100                                                                                 25
8307 207 307 100                                                                                 25
 207 307 303 100                                                                                 25
 307 303 340 100                                                                                 25
 303 340 341  88 346  12                                                                         25
 340 3468346 100                                                                                 25
MP34-42
 340 341 351 100                                                                                 25
 341 351 352  95 355   5                                                                         25
 351 352 371 100                                                                                 25
 352 371 372  94 375   6                                                                         25
 371 372 373 100                                                                                 25
 372 373 381 100                                                                                 25
 373 381 391  91 385   9                                                                         25
 381 391 411 100                                                                                 25
 391 4118411 100                                                                                 25
8345 245 345 100                                                                                 25
 245 345 341 100                                                                                 25
 345 341 351 100                                                                                 25
 351 3558355 100                                                                                 25
8356 256 356 100                                                                                 25
 256 356 352 100                                                                                 25
 356 352 371 100                                                                                 25
 371 3758375 100                                                                                 25
8376 276 376 100                                                                                 25
 276 376 372 100                                                                                 25
 376 372 373 100                                                                                 25
8377 277 377 100                                                                                 25
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 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 11
 306   11800  50                                                              37
 307   11800  48                                                              37
 345   1   0  97
 356   11800  40                                                              37
 376   11800  40                                                              37
 377   1   0  97
 395   11800  40                                                              37
MP30-34
8300 3004960   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
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8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 12
 306   11980  51                                                              37
 307   11980  49                                                              37
 345   1   0  97
 356   11980  40                                                              37
 376   11980  40                                                              37
 377   1   0  97
 395   11980  40                                                              37
MP30-34
8300 3005160   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69      74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                  74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                  74
 341 351   8 341 371   6 341 381   7 341 411  79                              74
 352 371   8 352 381   8 352 411  84                                          74
 372 381  12 372 411  88                                                      74
 373 381  12 373 411  88                                                      74
 391 411 100                                                                  74
                                                                             170
   0   8                                                                     210
MP30-34
8300 300 301 100                                                              25
 300 301 302  94 305   6                                                      25
 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
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 372 373 381 100                                                                 25
 373 381 391  91 385   9                                                         25
 381 391 411 100                                                                 25
 391 4118411 100                                                                 25
8345 245 345 100                                                                 25
 245 345 341 100                                                                 25
 345 341 351 100                                                                 25
 351 3558355 100                                                                 25
8356 256 356 100                                                                 25
 256 356 352 100                                                                 25
 356 352 371 100                                                                 25
 371 3758375 100                                                                 25
8376 276 376 100                                                                 25
 276 376 372 100                                                                 25
 376 372 373 100                                                                 25
8377 277 377 100                                                                 25
 277 377 373 100                                                                 25
 377 373 381 100                                                                 25
 381 3858385 100                                                                 25
8395 295 395 100                                                                 25
 295 395 391 100                                                                 25
 395 391 411 100                                                                 25
Time Period 13
 306   12160  51                                                                 37
 307   12160  49                                                                 37
 345   1   0  97
 356   12160  40                                                                 37
 376   12160  40                                                                 37
 377   1   0  97
 395   12160  40                                                                 37
MP30-34
8300 3005360   6                                                                 50
8306 206 360   4                                                                 50
8307 207 489   8                                                                 50
MP34-42
8345 2452159   9                                                                 50
8356 256 819   8                                                                 50
8376 276 400   5                                                                 50
8377 2771216  10                                                                 50
8395 295 430   9                                                                 50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69         74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                     74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                     74
 341 351   8 341 371   6 341 381   7 341 411  79                                 74
 352 371   8 352 381   8 352 411  84                                             74
 372 381  12 372 411  88                                                         74
 373 381  12 373 411  88                                                         74
 391 411 100                                                                     74
                                                                                170
   0   8                                                                        210
MP30-34
8300 300 301 100                                                                 25
 300 301 302  94 305   6                                                         25
 301 3058305 100                                                                 25
 301 302 303 100                                                                 25
8306 206 306 100                                                                 25
 206 306 302 100                                                                 25
 302 303 340 100                                                                 25
8307 207 307 100                                                                 25
 207 307 303 100                                                                 25
 307 303 340 100                                                                 25
 303 340 341  88 346  12                                                         25
 340 3468346 100                                                                 25
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MP34-42
 340 341 351 100                                                                                25
 341 351 352  95 355   5                                                                        25
 351 352 371 100                                                                                25
 352 371 372  94 375   6                                                                        25
 371 372 373 100                                                                                25
 372 373 381 100                                                                                25
 373 381 391  91 385   9                                                                        25
 381 391 411 100                                                                                25
 391 4118411 100                                                                                25
8345 245 345 100                                                                                25
 245 345 341 100                                                                                25
 345 341 351 100                                                                                25
 351 3558355 100                                                                                25
8356 256 356 100                                                                                25
 256 356 352 100                                                                                25
 356 352 371 100                                                                                25
 371 3758375 100                                                                                25
8376 276 376 100                                                                                25
 276 376 372 100                                                                                25
 376 372 373 100                                                                                25
8377 277 377 100                                                                                25
 277 377 373 100                                                                                25
 377 373 381 100                                                                                25
 381 3858385 100                                                                                25
8395 295 395 100                                                                                25
 295 395 391 100                                                                                25
 395 391 411 100                                                                                25
Time Period 14
 306   12340  52                                                                                37
 307   12340  50                                                                                37
 345   1   0  97
 356   12340  40                                                                                37
 376   12340  40                                                                                37
 377   1   0  97
 395   12340  40                                                                                37
MP30-34
8300 3005560   6                                                                                50
8306 206 360   4                                                                                50
8307 207 489   8                                                                                50
MP34-42
8345 2452159   9                                                                                50
8356 256 819   8                                                                                50
8376 276 400   5                                                                                50
8377 2771216  10                                                                                50
8395 295 430   9                                                                                50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69                        74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                                    74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                                    74
 341 351   8 341 371   6 341 381   7 341 411  79                                                74
 352 371   8 352 381   8 352 411  84                                                            74
 372 381  12 372 411  88                                                                        74
 373 381  12 373 411  88                                                                        74
 391 411 100                                                                                    74
                                                                                               170
   0   8                                                                                       210
MP30-34
8300 300 301 100                                                                                25
 300 301 302  94 305   6                                                                        25
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 301 3058305 100                                                              25
 301 302 303 100                                                              25
8306 206 306 100                                                              25
 206 306 302 100                                                              25
 302 303 340 100                                                              25
8307 207 307 100                                                              25
 207 307 303 100                                                              25
 307 303 340 100                                                              25
 303 340 341  88 346  12                                                      25
 340 3468346 100                                                              25
MP34-42
 340 341 351 100                                                              25
 341 351 352  95 355   5                                                      25
 351 352 371 100                                                              25
 352 371 372  94 375   6                                                      25
 371 372 373 100                                                              25
 372 373 381 100                                                              25
 373 381 391  91 385   9                                                      25
 381 391 411 100                                                              25
 391 4118411 100                                                              25
8345 245 345 100                                                              25
 245 345 341 100                                                              25
 345 341 351 100                                                              25
 351 3558355 100                                                              25
8356 256 356 100                                                              25
 256 356 352 100                                                              25
 356 352 371 100                                                              25
 371 3758375 100                                                              25
8376 276 376 100                                                              25
 276 376 372 100                                                              25
 376 372 373 100                                                              25
8377 277 377 100                                                              25
 277 377 373 100                                                              25
 377 373 381 100                                                              25
 381 3858385 100                                                              25
8395 295 395 100                                                              25
 295 395 391 100                                                              25
 395 391 411 100                                                              25
Time Period 15
 306   12520  53                                                              37
 307   12520  51                                                              37
 345   1   0  97
 356   12520  43                                                              37
 376   12520  42                                                              37
 377   1   0  97
 395   12520  40                                                              37
MP30-34
8300 3005760   6                                                              50
8306 206 360   4                                                              50
8307 207 489   8                                                              50
MP34-42
8345 2452159   9                                                              50
8356 256 819   8                                                              50
8376 276 400   5                                                              50
8377 2771216  10                                                              50
8395 295 430   9                                                              50

MP30-42 OD Table
 300 301    6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69       74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                    74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                    74
 341 351   8 341 371   6 341 381   7 341 411  79                                74
 352 371   8 352 381   8 352 411  84                                            74
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 372 381  12 372 411  88                                                       74
 373 381  12 373 411  88                                                       74
 391 411 100                                                                   74
                                                                              170
   0   8                                                                      210
MP30-34
8300 300 301 100                                                               25
 300 301 302  94 305   6                                                       25
 301 3058305 100                                                               25
 301 302 303 100                                                               25
8306 206 306 100                                                               25
 206 306 302 100                                                               25
 302 303 340 100                                                               25
8307 207 307 100                                                               25
 207 307 303 100                                                               25
 307 303 340 100                                                               25
 303 340 341  88 346  12                                                       25
 340 3468346 100                                                               25
MP34-42
 340 341 351 100                                                               25
 341 351 352  95 355   5                                                       25
 351 352 371 100                                                               25
 352 371 372  94 375   6                                                       25
 371 372 373 100                                                               25
 372 373 381 100                                                               25
 373 381 391  91 385   9                                                       25
 381 391 411 100                                                               25
 391 4118411 100                                                               25
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 245 345 341 100                                                               25
 345 341 351 100                                                               25
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8356 256 356 100                                                               25
 256 356 352 100                                                               25
 356 352 371 100                                                               25
 371 3758375 100                                                               25
8376 276 376 100                                                               25
 276 376 372 100                                                               25
 376 372 373 100                                                               25
8377 277 377 100                                                               25
 277 377 373 100                                                               25
 377 373 381 100                                                               25
 381 3858385 100                                                               25
8395 295 395 100                                                               25
 295 395 391 100                                                               25
 395 391 411 100                                                               25
Time Period 16
 306   12700  54                                                               37
 307   12700  52                                                               37
 345   1   0  97
 356   12700  44                                                               37
 376   12700  41                                                               37
 377   1   0  97
 395   12700  40                                                               37
MP30-34
8300 3005960   6                                                               50
8306 206 360   4                                                               50
8307 207 489   8                                                               50
MP34-42
8345 2452159   9                                                               50
8356 256 819   8                                                               50
8376 276 400   5                                                               50
8377 2771216  10                                                               50
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8395 295 430   9                                                                   50

MP30-42 OD Table
 300 301   6 300 340  11 300 351   3 300 371   5 300 381   6 300 411  69       74
 302 340  13 302 351   2 302 371   5 302 381   6 302 411  74                   74
 303 340  14 303 351   2 303 371   5 303 381   6 303 411  73                   74
 341 351   8 341 371   6 341 381   7 341 411  79                               74
 352 371   8 352 381   8 352 411  84                                           74
 372 381  12 372 411  88                                                       74
 373 381  12 373 411  88                                                       74
 391 411 100                                                                   74
                                                                              170
   1                                                                          210
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