MINNESOTA DEPARTMENT OF TRANSPORTATION

Research

Technical Support for
Implementation of
Freeway Network Simulation Software

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16. Abstract (Limit: 200 words)

This report summarizes the results from the technical support and testing of the freeway traffic simulation software developed at the University of Minnesota.

The University's civil engineering department developed and implemented an experimental course that addressed fundamental theories in traffic flow modeling and simulation. They also incorporated a set of an online help manual into simulation software.

Software testing was conducted through two sets of case studies involving the high-occupancy vehicle (HOV) lane and ramp metering simulation modules. The HOV lane case study used a 10-mile section of the westbound I-94 freeway with an additional lane and evaluated the performance of alternative HOV lane strategies with different sets of demand and HOV proportions. For the same amount of total demand without assuming induced trips, the higher HOV proportion, the smaller the mainline delay.

The ramp metering case study compared the performance of the current Mn/DOT metering policy with that of a no-metering option for a 16-mile section of the northbound 169 freeway with 20 percent higher demand than the current level. The metering case study showed that the total system delay, including both mainline and ramps, was significantly reduced when the ramps were controlled compared to a no-metering case for a given set of demand.

The case studies indicate that the simulation software can be applicable in evaluating alternative design and operational strategies for a given set of demands.

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TECHNICAL SUPPORT FOR IMPLEMENTATION OF FREEWAY NETWORK SIMULATION SOFTWARE

FINAL REPORT

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TABLE OF CONTENTS

List of Tables

List of Figures

EXECUTIVE SUMMARY

This report summarized the final results of the technical support research project to implement freeway traffic simulation software developed at the University of Minnesota. First, an experimental course was developed and implemented at the University of Minnesota for undergraduate students and traffic engineers. The course covered the fundamental theories in traffic flow modeling and simulation. Further, a set of metering case studies was conducted as class projects using the freeway simulation software supported in this research. To facilitate the application of the simulation software, an on-line help manual was also developed and incorporated into the software.

The simulation software was tested in this research through two sets of case studies involving the HOV lane and ramp metering simulation modules. The HOV lane case study used a 10-mile section of the westbound I-94 freeway with an additional lane and evaluated the performance of alternative HOV lane strategies with different sets of demand and HOV proportions. As expected, for the same amount of total demand without assuming induced trips, the higher HOV proportion the smaller the mainline delay and it was possible to identify the value of HOV proportion value that makes the mainline delay zero. The ramp metering case study compared the performance of the current Mn/DOT metering policy with that of no-metering option for a 16-mile section of the northbound 169 freeway with increased demand, i.e., 20% higher than the current level. The metering case study showed that the total system delay, including both mainline and ramps, was significantly reduced when the ramps were controlled compared to no-metering case for a given set of demand. The above case studies indicate that the simulation software can be applicable in evaluating alternative design and operational strategies for a given set of demand.

I.   INTRODUCTION

I. 1 Background

Traffic simulation has long been recognized as one of the most effective tools in evaluating the effectiveness of various operational and design alternatives prior to implementation.   To address the above issue, a research team at the University of Minnesota has developed a personal-computer based, freeway network simulation software, which has been designed specifically for the operational needs of the Minnesota Department of Transportation (Mn/DOT).   While the development phase of the simulation model was completed, the effective implementation of the software required technical support and continuous debugging/maintenance of the model.   This report summarizes the results from such a technical support and model enhancements. The main objectives of the project include:

- Development and implementation of a technical course for freeway network simulation
- Development of a user manual and on-site technical support for implementation
- Continuous debugging and maintenance of the simulation software.

I.2 Report organization

Chapter II briefly describes the outline of the technical course developed in this project to support freeway network simulation.   This course was offered to the students and engineers in Fall 1998 at the Civil Engineering Department, University of Minnesota.   The on-line help manual was developed in Chapter III. Chapter IV includes the enhancement and testing results of the Mn/DOT ramp metering module that adopts a zone-based traffic responsive control algorithm. A 16-mile section of the northbound 169 freeway was used for this testing, which used a set of real traffic data for calibrating model parameters. The application results of the High Occupancy Vehicle (HOV) lane simulation module are included in Chapter V. Finally Chapter VI includes conclusions.

II.   DEVELOPMENT AND IMPLEMENTATION OF A TECHNICAL COURSE FOR FREEWAY NETWORK SIMULATION

II. 1 Course objectives

The main objective of the technical course developed in this research is to support freeway network simulation by introducing the basic theory on traffic flow modeling and simulation as well as by addressing practical issues with current freeway traffic management and operations.   Specific focus was on the basic concepts and state-of-the-art strategies on ramp metering.   Further, hands-on application of traffic simulation for addressing freeway management issues was also included as a part of course activities.   Current Twin Cities' ramp metering system was used as an example system and its algorithm/current operational issues were discussed.   In particular, a macroscopic traffic simulation software, developed at the University of Minnesota, was used as a tool to evaluate and design alternative management strategies.   Each student was required to conduct a class project that was designed to address at least one issue in current freeway traffic management.

II.2 Course outline

The outline of the course contents and schedule, originally designed for a one-quarter course and implemented in Fall 1999, is as follows (Appendix A includes the course syllabus);

Week 1: Introduction freeway traffic management
        9/28: "Overview of Twin Cities Freeway Management System"
            Guest lecturer : Glen Carlson, Director, Traffic Management Center, Mn/DOT
        9/30: Operational issues in freeway traffic management

Week 2: Introduction to traffic simulation

        10/5: Basic concepts in traffic simulation and overview of current modeling approaches
        10/7: Introduction to macroscopic simulation software: Lab experimentation

Week 3 : Freeway Ramp Metering Systems

        10/12: Basic concepts and Architecture of Mn/DOT algorithm
            (Guest lecturer: Rich Lau, TMC)
        10/14: Current zone structure and metering parameters
            (Guest lecturer: Rich Lau, TMC)

Week 4: Freeway Ramp Metering Systems (continued)

> 10/19: Performance of current Mn/DOT algorithm
> (Guest lecturer: John Bieniek, TMC)
> 10/21: Flow conservation and continuum flow theory

Week 5: Introduction to macroscopic modeling of traffic flows
> 10/26: Input data preparation for class project (geometry data)
>
> 10/28: Input Data preparation for simulation (traffic data)

Week 6: Testing and calibration of Macroscopic simulation

> 11/2: Input data preparation for simulation (continued)
>
> 11/4: Testing and calibration of Kronos simulation model/ output interpretation

Week 7: Shock wave theory and applications

> 11/9: Shock wave theory and applications (I)
>
> 11/11: Shock wave theory and applications (II)

Week 8: Queuing Theory and applications / Ramp metering simulation

> 11/16: Queuing theory and applications
>
> 11/18: Queuing theory and applications (II)/ Preparation for ramp metering simulation
>
> (Due: *1ˢᵗ Interim report for class project*)

Week 9: Evaluation of ramp metering schemes with simulation, Capacity issues

> 11/23: Simulation of ramp metering and analysis of output
> 12/25: Capacity and bottlenecks (I)

Week 10: Capacity and bottlenecks, ITS Architecture
> 11/30: Capacity and bottlenecks (II)
> 12/2 : Overview of ITS Architecture

Week 11: Final exam and Presentation of class projects

> 12/7: Final exam
> 12/9: Class project presentation and discussion
> *(Final report for class project due)*

As indicated above, the engineers at the Traffic Management Center (TMC), Mn/DOT, participated in this course as the volunteer guest lecturers.

III. DEVELOPMENT OF ON-LINE HELP MANUAL

III.1 Overview

The user interface of the Kronos simulation software allows a user to create and edit input data files interactively using 'data-windows'. Further, the output from simulation can be viewed in the spread-sheet or graphical mode through the interface. In this chapter, a set of the on-line help manual is developed and a detailed description of the required data for each data window is incorporated into the software. The following sections describe the on-line help manual for both input and output data windows.

III. 2 On-line Help for Main Menu

Overview of Data Input Process

The data required for Kronos includes freeway geometry, traffic demand at upstream boundary and entrance/exit ramps, external boundary conditions, metering control options, and global simulation parameters. The recommended process for entering data is as follows:

Step 1) Build a freeway section on the screen with the geometry icons in Tools window.

Step 2) For each geometry segment, enter geometric and demand data using sub-windows
   (double click left mouse button to open sub-windows)

Step 3) Enter values for the global parameters using Edit_Parameter window.

Step 4) Select metering control option from Metering_Option window.

Step 5) Save data with a case name. Kronos creates a subdirectory with the same case
   name and store all the input files in the case subdirectory.

Step 6) Run simulation by selecting Simulation-Run option.
   (simulation output will be saved in the same case subdirectory.)

Step 7) Analyze simulation output with spreadsheet, 2/3-D graphs and animation format.

Building a freeway section on the screen

KRONOS has 12 different geometric segment types that can be used to construct the freeway geometry. They are pictured in the far-left window of the screen. The first segment needs to be a pipeline. Select an appropriate segment type by clicking on the segment's picture in the far-left

Tools window. Between two non-pipeline segments, such as a segment containing an on ramp, merge area, etc., there must be a pipeline segment. The program will prompt you for a pipeline in such a case.

Delete Button: When this button is clicked on it will delete the highlighted segment on the main screen.

Replace Button: After clicking on this button, you may click on the new segment you want from the tools window and it will then replace the highlighted segment.

Insert Button: After clicking this button, you can add in a new segment from the tools window and it will be inserted after the segment that is highlighted.

Entering geometry and demand data

Specify the physical and demand information by double clicking on the segment that has been created on the freeway section. It is recommended to draw out the segments on a paper and number them or else on a map containing the freeway section to be simulated.

File Open/Save

It is strongly recommended to save the data before you run simulation. File->Save As command will prompt you to enter a name for the case created. The program will create a subdirectory with the case name and store all the input files for the case in the same subdirectory. When an existing case is opened, "Save" option stores all the data in the same subdirectory with the same case name.

Edit Parameters

This option allows user to enter or modify the values of all the global parameters for a given freeway. The types of the simulation parameters include: start and end times, types of desired output, external boundary conditions for a given freeway, global flow-density relationship, and metering control options. The detailed description for this option is included in the Edit_Parameter sub-window.

How to Run Simulation

After all parameters have been entered into the program simulation can begin. Select RUN from the Simulate pull down menu. If there is an error, for example, missing data, it will inform you. You must make the change necessary and simulate again. The output files will be stored in the same directory as the input files.

Output Options

The following output options are available with the current version.

Spread Format

Detailed output values of flow rate, density and speed for each time interval every 100 feet in a spread sheet format, which can be saved and imported by commercial spreadsheet software.

Total Value- Total flow and density values for each 100 ft segment.

Lane by lane value- This format allows user to view flow, density and speed values for each lane for each time interval. The direction of flow is from top to bottom.

Graphical Output

A 2D or a 3D plot of speed, flow, and density as a function of time or distance, or both.

Animation

Time-dependent variations of flow rate, density and speed levels can be viewed in different colors through time for a given section of freeway.

III.3 On-line Help for Edit_Parameter Screen

Simulation Parameters

Date: date in the form: YYMMDD.

Start Time: Start time of the simulation.

End Time: Ending time of the simulation.

Demand Time Slice Duration: Time increment duration, in minutes, for specifying traffic demand. This value affects the number of time slices that user enters the demand for each entrance and exit.

Output Data Aggregation Period: Output aggregation time interval in minutes.

HOV Start and End Time: Time period during which HOV lanes are operated. You will then be able to enter the demand of HOV in the demand tab in the segment parameter screen.

Output Options

Check each box as it applies to each individual simulation.

Instantaneous Output:

This gives the output exactly at the time increment that was specified in Output Data Aggregation Period. For example, if a time slice for output was specified to be 5 minutes then the output will give data exactly at 0 min., 5 min., 10 min., etc.

Time Average Output:

This will average the output over the time period specified in Output Data Aggregation Period. For example, if the time slice for output were specified to be 5 minutes then the output would be averaged over each time slice. So it will give an average for 0 to 5 minutes, 5 to 10 minutes, etc.

Measure of Effectiveness (MOE's):

If this box is checked then the simulation will calculate MOE's including vehicle hours, vehicle miles and delay.

Station Detector Output:

If this option is checked, then the simulation will allow the user to retrieve the data from each detector station entered in the program. The detector stations can be entered in the segment data screen.

Boundary Conditions

Mainline Demand Flow Condition:

This is important for simulation, since finding the correct value on the Q-K curve depends on if the flow at both upstream and downstream boundaries are congested or not.

Upstream Boundary Arrival Flow

Flow Congestion Condition Specification: Check if the congestion condition of the flow arriving at the upstream boundary is going to be specified. This option is generally used to calibrate the simulation module with real data.

Downstream Boundary Exit Flow Condition

No Specification: Assumes free flow condition at the downstream boundary

Exit Flow/Capacity Specification: when only the amount of exit flow will be specified.

Exit Flow and Congestion Condition Specification: when both amount and congestion condition of exit flow will be specified.

Entrance Ramp Upstream Boundary

Flow Congestion Condition Specification: when congestion condition for the flow arriving at the upstream boundary of each entrance ramp will be specified.

Exit Ramp Downstream Boundary

Exit Congestion Condition Specification: when congestion condition of the flow exiting at the downstream boundary of each exit ramp will be specified.

Global Q-K (flow-density) curve parameters

The global flow-density relationship is used as the base flow-density relationship for a given case. The current version requires 5 data points to construct the base relationship that is modeled as a combination of three curves.

Q_{max}: maximum flow per lane per hour.

K_{cr} : critical capacity in vehicles per mile.

Q_a :   Flow at @ Free Flow Speed (FFS):

FFS: free flow speed

K_{jam}: Jam Density per lane.

PLOT : Click on this button and the plot will show an updated plot of the new above parameters listed above.

Metering Options

Currently two types of ramp metering are available for simulation, i.e., Fixed metering and Automatic Rate Selection Metering (ARS). ARS metering emulates the current Mn/DOT algorithm, as of December 1999, being implemented by the Traffic Management Center on most freeways in the Twin Cities Metro area. Depending on the type of metering operation selected

for simulation, user can enter the values of global metering parameters necessary for the selected metering option.

Non-Metering: Check this box if the simulation does not include ramp metering.

Fixed Metering: If this choice is checked, a box of parameters appears in the upper right corner. In this box, you may enter the time interval that the metering rate should be updated. Also enter start and end times of metering operation. The specific, time-variant metering rates for each entrance ramp can be entered at Segment Screen. This option does not require detector specification.

Automatic Rate Selection:

The global parameters for the Automatic Rate Selection metering option is as follows;

Rate Change Interval: Time interval that metering rate should be updated.

Mainline Data Aggregation Interval: Time interval for collecting and aggregating mainline detector data for metering.

Ramp Data Aggregation Interval: Time interval for collecting and aggregating ramp detector data.

System Time Delay: Time delay between the time that the metering rate is calculated and the time that the metering rate is implemented.

Turn-on Condition Check Interval: Duration of the time period that the system will check freeway condition to turn on meters.

Turn-off Condition Check Interval: Duration of the time interval that the system will check freeway condition to turn off meters.

III. 4 On-line Help for Segment Data Windows

This screen is unique for each segment of a given freeway. Depending on the type of a selected segment, the user can enter geometry data, it's Q-K Curve parameters, traffic demand, location and ID of detectors, incidents, and metering option.

Geometry data window:
Segment Name: It is advantageous to have a name for each segment for future references. Examples would be the name of a cross street, mile marker, or entrance/exit ramp.

Main Length (L): The dimension of the part of the segment, which consists solely of the main freeway through lanes. (Most lengths are defined in a picture on each segments' parameter screen)

Initial Flow: This is the flow that enters each segment at the start of simulation.

Congested?: Check this box if the flow into the section is congested. This allows the simulation program know where on the Q-K curve the flow is located.

An Off-Ramp segment will require the following additional information:

Off Ramp Length (B): Specifies the length of an off ramp including a deceleration lane.

Lane Capacity: This is the lane capacity of the off ramp.

Initial Flow: This is the flow at the start of simulation. Check the box next to this to specify if this flow is congested.

Exit Capacity Restriction: Check this option if the capacity of the downstream end of an exit ramp is restricted.

An On-Ramp segment will require the following information:

On Ramp Length (A): specifies the length of the on ramp, including the acceleration lane.

Lane Capacity: This is the lane capacity of the on ramp.

Initial Flow: This is the flow at the start of simulation. Check the box next to this to specify if this flow is congested.

Meter Controlled?: Check this box if during simulation this entrance ramp is metered.

Meter Location: Distance of a meter from the upstream end of an entrance ramp.

Meter ID: Meter identification number in alphanumeric format.

HOV Start/End: Click on the HOV Start Button to indicate that a HOV lane begins at this segment. At a downstream segment where the HOV lane ends, click the HOV End Button.

Del to End: This button can be used to delete a HOV section previously defined.

Q-K Curve data window

To use the global QK Curve values specified in the Global Parameters Tab check the button at the top. Otherwise, enter the specific values for this segment.

Demand data window

This window is the place to enter the traffic demand data for each entrance and exit ramp in a given freeway section. If the Factor Button is clicked on, a screen will pop up that asks what factor you would like to multiply each data entry by. Any segment that does not have either on or off ramp will have a blank Demand window.

Edit Detectors window

This tab has four choices: Main Lane, On Ramp, Off Ramp, and Auxiliary Lane. Click on the circle that you want to enter or edit existing detector information. For example, in on-ramp segments user can specify detectors at both mainline and ramp segments. In the case of auxiliary lane segments, the mainline choice will be blank.

Station ID: Station ID in numeric number. The information below the ID box is specific to the Detector Station ID showing in the white box.

Maximum number of main lane detectors in this station: This corresponds to the number of lanes in the freeway segment. If there are two lanes in the segment then there is only room for two detectors in a station.

Distance from the beginning of the segment: Enter in feet that the station is located from the start of the segment.

Critical Occupancy: The occupancy value corresponding to the maximum volume observed at the detector station.

Conversion Parameters: The following parameters are used in the simulation model to estimate occupancy and available space from the simulated density values. The occupancy values are used by the ramp metering module.

    Occupancy/Density conversion factor (k/occ)

    Available Space Estimation Factor

Detector Information: This is the place to enter the specific ID's for each lane detector included in the detector station. If it is desired to enter another detector station in a segment, then the button next to the Station ID box, "Next Station," can be clicked and a new ID can be entered for the second station in the segment.

Incident data window

Check the 'Incident Here' box if there is an incident needs to be placed on the current segment. If the incident needs to be deleted, then the Remove Incident Button may be clicked.

Rate Selection Metering data window

Occupancy station assignment

Number of Occupancy Stations: Enter the number of occupancy stations assigned for the current meter. Then enter the Occupancy Station ID's below.

Number of Occupancy Thresholds: Enter the number of occupancy thresholds used for the occupancy control mode in the Rate Selection Metering. For example, in order to have 6 metering rates, there should be five occupancy thresholds. When the fifth threshold is met, the meter will be in Rate 6. The red times for each rate should be entered below.

Ramp Metering Periods

This window is best explained with an example. For example, if the simulation time is from 14:00 until 19:30. However, metering is only desired from 15:00 until 19:00, then the information would be entered in as:

Period	Start Time	Non-Metering	Turn-on	ARS	Turn-off	Fixed-Rate
1	14:00	X				
2	15:00		X			
3	15:30			X		
4	18:30				X	
5	19:00	X				

This example shows that the first period, from 14:00 until 15:00, does not have metering. Beginning at 15:00 the meters will start to turn on according to the thresholds. At 15:30 all the meters will be forced on and the metering will continue until 18:30. At 18:30, the meters will begin the turn-off phase and will be forced off by 19:00.

13

Fixed Metering Rate data window

This window will be activated only when the user selects Fixed Metering option in the main menu. For a meter with fixed metering option, user needs to enter metering rates (vehicles per hour) for each time interval for the entire simulation period.

III.5 On-line Help Manual for Output Data Screens

The simulation results from Kronos are stored in a set of output files for each 'output-aggregation' time interval specified by a user in the 'Edit_Parameter' screen. The current version of interface retrieves those output files after a simulation is completed and show them in either a spreadsheet or graphical format. In the spreadsheet option, the simulation results of each 100 ft segment can be seen for both mainline and ramps. Each spreadsheet can be saved and opened later with commercial spreadsheet software, such as Excel. Currently, two types of output are available in the spreadsheet format; total and lane-by-lane output.

Total value in a spreadsheet format

The following output types are currently available.

Aggregated output

> *Total Flow*: Sum of all lane flows in each 100ft segment during each time interval.

> *Total Density*: Sum of all lane densities during each time interval.

Instantaneous lane-average output

> *Inst_Lane_Avg_Flow*: Instantaneous lane average flow rate, i.e., the simulated flow rate vale at the beginning instant of each time interval. For example, if the output aggregation time interval is 5 minutes, then the lane average flow rates at 0, 5th, 10th --- minute will be provided.

> *Inst_Lane_Avg_Density*: Instantaneous average lane density given in the same format as above.

> *Inst_Lane_Avg_Speed*: Instantaneous lane average speed given in the same format as above.

Time-average lane-average output

Simulation results averaged for each time interval for all lanes in each 100 ft segment.

> *Avg_Lane_Avg_Flow*: Lane average flow rate for each 100 ft segment during each time interval.

> *Avg_Lane_Avg_Density*: Lane average density in the same above format

14

Avg_Lane_Avg_Speed: Lane average speed in the same above format

Measures of Effectiveness (MOEs) for each 100 ft segment every time interval

Veh-hrs/time interval: Total vehicle hours of all the lanes in each 100 ft segment during each time interval.

Veh-miles/time interval: Total vehicle miles of all the lanes in a 100 ft segment during each time interval.

Delay/time interval: Total delay of all the lanes in a 100 ft segment during each time interval. Delay is defined as the vehicle hours of those whose speed levels are below the threshold value pre-specified by a user.

Cumulative Veh-miles: Total vehicle miles of each 100 ft segment accumulated up to each time interval.

Cumulative Delay: Total delay of each 100 ft segment accumulated up to each time interval.

Unused Capacity/time interval: The unused capacity during each time interval.

Lane-by-Lane output in spreadsheet format

Kronos also provides lane-by-lane output values in a spreadsheet format, which represents the lane configuration of a given freeway with columns in a spreadsheet. For example, for each time interval, the simulation results of a right most lane are stored in the first column in a spreadsheet, whose second column has the output of the next lane left of the rightmost lane. In the current version, only Flow rate, Density and Speed values of each 100 ft segment are available in either 'instantaneous' or 'time-average' format for each output aggregation time interval.

Graphical output

In the current version, all the output types available in the 'Total value' spreadsheet option can be viewed either three or two-dimensional graphical format. Further, a two-dimensional contour plot can be drawn for the same output type. The 'animation' option allows a user to observe the lane-by-lane variations of simulated flow rate, density and speed values for each 100 ft segment in a mainline through time for the entire simulation period.

IV. ENHANCEMENT AND TESTING OF TRAFFIC RESPONSIVE RAMP METERING MODULE

IV.1 Overview of Mn/DOT Metering Algorithm

In this chapter, the new ramp metering simulation module that emulates the current Mn/DOT 97 algorithm is enhanced and a case study is conducted using a set of real data collected from a section of the northbound 169 freeway. The algorithm is based on the same zone-based metering concept as the previous one, but reflects available space in each zone in determining metering rates and uses the exit volume data measured in real time. Further, it has the capability to use the variable capacity values at the bottleneck locations. The main features of the Mn/DOT 97 algorithm include

♦ each ramp has 6 predefined rates, i.e., red times, and volume and occupancy thresholds,

♦ all the metered ramps within a zone have same volume thresholds and volume detector station, i.e., station A (upstream boundary detector station),

♦ every 30 seconds, two rates are selected based on volume and occupancy thresholds,

♦ Occupancy control is same as the old one.

Let   Mt : Sum of Metering rates for all the ramps metered during time interval t within zone i

   Ft : Sum of freeway to freeway metering rates during t within zone i

   Ut : Sum of entering volume from all un-metered ramps during t within zone i

   Xt : Sum of exit ramp volume for all the exit ramps during t within zone i

   At: Upstream boundary measured volume during t

   Bi : Capacity of bottleneck B of zone i
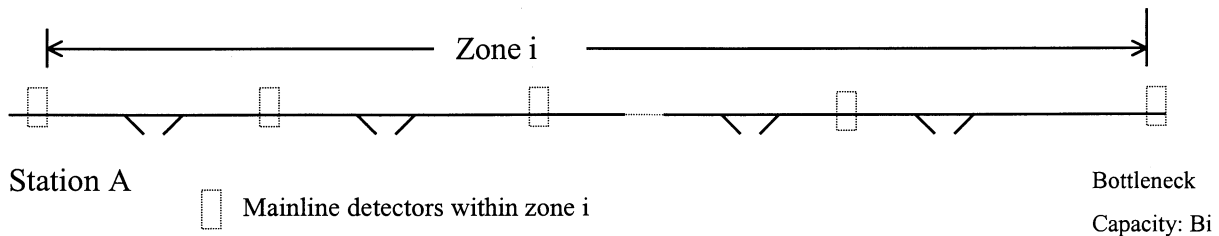

Figure 4-1. Typical configuration of a metering zone

17

Then applying the flow conservation principle to the zone i results in the following flow balance equation:

$$(Mt + Ft)i = Bi - At - Ut + Xt + St \qquad (4-1)$$

where, $St =$ "Zone Capacity" $- \sum[(Oc_t)_1 * alpha_1 * (\text{number of lanes at }_1)]$

Zone capacity = zone-specific input parameter indicating the number of vehicles in a zone when it is "full" with vehicles.

1 = mainline detector station within a zone between upstream and downstream boundaries, i.e., not including both end stations.

Oc_t = Occupancy measurements from detector l during t interval

$alpha_1$ = Conversion parameter for detector l (input parameter with a default value of 1.1)

Bi = Bottleneck capacity (input parameter for zone boundary detector station)

The zone-based metering control tries to balance the flow in each zone by determining the total input to zone i, i.e., $(M + F)i$, that equals to the right-hand-side of the equation 4-1. In the above equation all the values are 5-minute values. However, A_t is a 5-min converted volume using a set of previous 30-second data (number of 30 sec intervals is an input parameter and is called smoothing factor for A_t). E.g. let v_0 is the last 30 sec. volume and v_1, the previous 30 second data, etc. If "Smoothing factor" is 5, then

5-Minute converted volume $At = (v_0 + v_1 + \ldots + v_6) / 6 * 10$

Further, St = number of vehicles calculated with previous 30 second occupancy data.

Ut, Xt = currently, previous 5-min measurements are used.

Metering rate determination in real time with zone control

Each metered ramp is assigned six metering rates, which would equate to 1.5, 1.3, 1.1, 0.9, 0.7 and 0.5 times the target volume for that ramp over a 5-minute time period. Similar rates on freeway to freeway ramps would be 1.25, 1.15, 1.05, 0.95, 0.85 and 0.75 times the target volume. The selection of which rate to use is based on a comparison of the sum of the measured values, i.e., $Vi = Bi - At - Ut + Xt + St$, to a series of thresholds as follows;

Rate 1	Rate 2	Rate 3	Rate 4	Rate 5	Rate 6

$(Bi-At-Ut+Xt+St) \geq$ 1.4M +1..2F   1.2M +1..1F   1.0M +1..02F   0.8M +0.9F   0.6M +0.8F

where, M = sum of target volumes for normal ramps,

F = sum of target volumes for freeway to freeway ramps.

The above six rates are converted to red times with the use of fixed yellow and green times of 1.3 and 0.7 seconds.

Occupancy control

The above algorithm depends on the traffic conditions at each zone bottleneck, i.e., the predefined bottlenecks remain as the controlling locations. However, during unusual traffic conditions or any incident periods, other locations could become bottlenecks. In those situations, the occupancy values measured every 30 second increments across all lanes in a station are used to determine the metering rates for each ramp. Each metered ramp is assigned detector stations up to three miles downstream for occupancy control. The highest occupancy measured for one minute at any station is compared to the following series of occupancy thresholds;

Measured Occupancy value	Rate level
< 17%	3
18	4
23	5
> 40	6

If the rate selected based on occupancy thresholds is more restrictive than the volume control rate, then it will be used for the next 30 second interval.

Meter Turn on condition

Every 5 minutes, measure M and F, i.e., sum of total entered volume from metered ramps, and

if $(M+F)_i >$ beta $* (B - A - U + X + S)_i,$

then turn on all the meters in zone i. 'beta' is an input parameter (default value is 0.85)

19

Meter Turn off condition:

For each ramp, if actual volume entered in the previous 5-min. interval is less than gamma * (total metering rate for last 5 minute interval), then turn off the meter. 'gamma' is an input parameter (default value is 0.85). While the above algorithm has been incorporated into the Kronos simulation module, its implementation in the field is still in progress.

IV. 2 Structure of metering simulation module

Kronos metering module was designed such that updating of an existing control strategy or adding a new strategy could be achieved with ease. At the end of each simulation time step, i.e., one second, traffic simulation module passes the control to the detection module, which finds the flow rate at the detector location at that particular time instance. These values are accumulated over 30-second and 5-minute periods for use by the metering module, which computes new rates for each meter every 30 seconds with those simulated detector values. The metering module then passes these rates to the simulation module either instantaneously or after a "system delay" period, if it exists. The data structure hierarchy and connection scheme used in the metering control module is shown in Figures 4-2 to 4-4.

IV. 3 Case study with metering module

In this research, a case study was conducted to test the ramp metering simulation module. A section of the northbound 169 freeway in the Twin Cities' metro area, which is frequently congested during afternoon peak periods, was selected for this study in cooperation with the engineers at TMC. The selected freeway section, which is 16.1 mile long with 28 entrance and 28 exit ramps, starts from Valley View Road and ends at Highway 77. Most of these entrance ramps in this section are metered both during morning and evening peak periods. The detailed geometry of the selected freeway is shown in Figure 4-5.

20

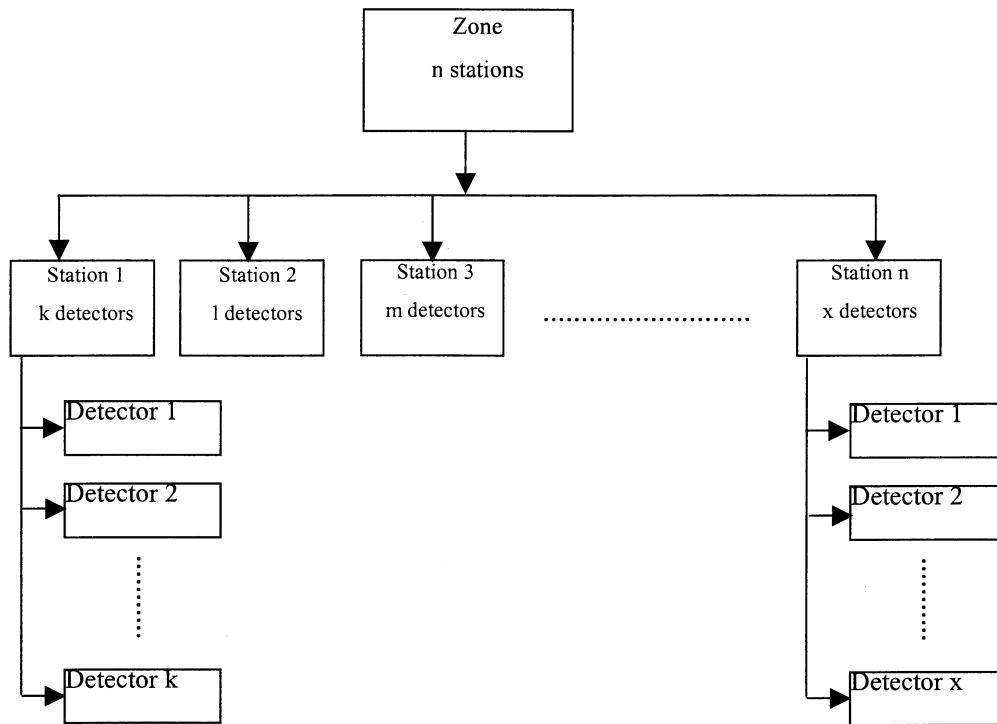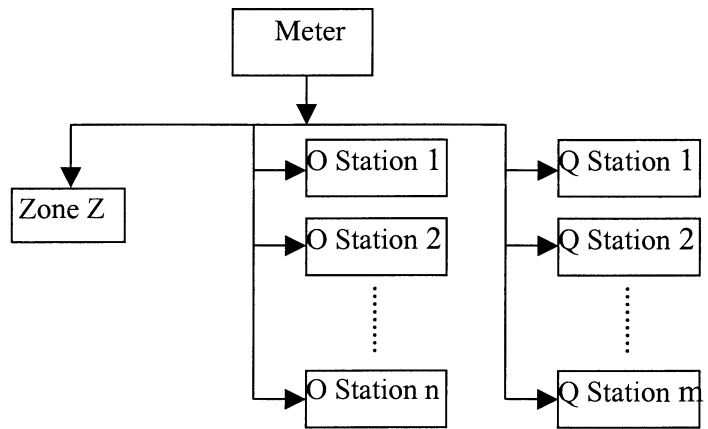Figure 4-2 Zone data structure

Figure 4-3 Meter data structure with n occupancy stations and m volume stations

Meter
Pointer

Zone
Pointer

Station
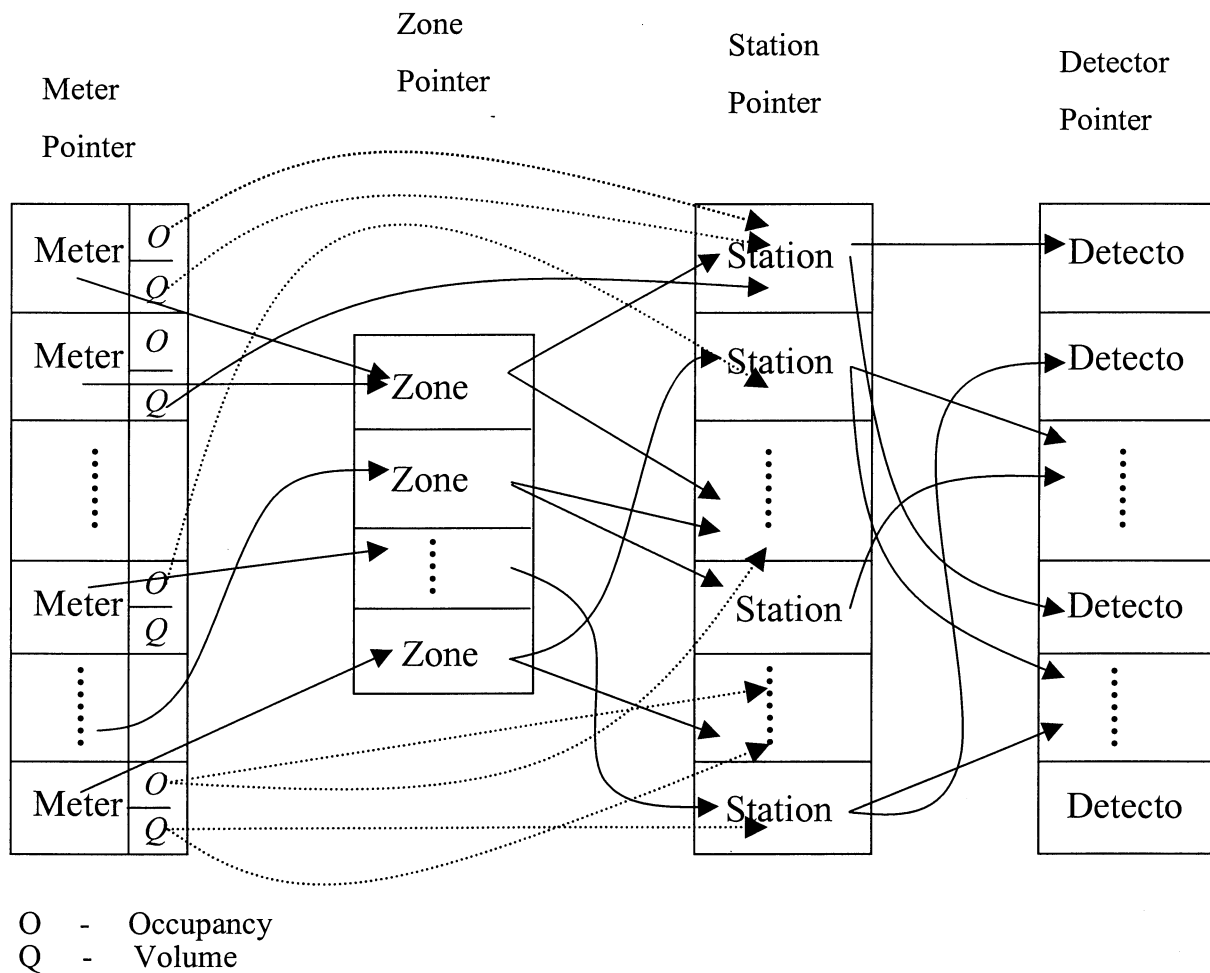Pointer

Detector
Pointer

O - Occupancy
Q - Volume

Figure 4-4 Connection between different data

The selected section was simulated using the data collected from the afternoon peak period, 2:00p.m. - 8:00p.m., of Wednesday, Oct 1, 1997. A mid week day was selected to better represent the traffic flow patterns. This particular day was chosen because it did not involve any non-recurring congestion due to incidents. About four mainline stations and five ramp detectors produced defective measurements. Minor corrections were made to their volume counts, such that the conservation principle would be met for these stations. Since the ramp detectors are located after the meters, only the metered volumes are known and not the actual demand.

First, the simulation module was calibrated for the selected section by adjusting the capacity values of each segment to minimize the differences between measured and simulated mainline volumes at the detector locations. For the calibration purpose, the metered volumes are used as demand and two simulations were done with and without metering (Case 1 and Case 2 respectively). As can be seen from Figure 4-6, the simulation has produced very similar results in both these cases. Since, the metered volumes, i.e., the flow that actually entered the freeway, were used as demand, it is expected that there should not be any delay at the entrance ramps in the test section. This observation can be made by looking at the results in Table 4-1 corresponding to Cases 1 and 2. From the results, it can be seen that the cumulative veh-mile values for both mainline and ramp regions is almost the same in both the cases. However, the delay on ramps in Case 2 is much higher than that of Case 1. The discrepancy in the results can be attributed to the following reasons:

♦ metering rates are often over-ridden by the TMC operators under heavy traffic on the ramps

♦ possible error in estimation of missing data values at faulty detector stations, and

♦ due to the approximations used in implementing the simulation model.

To test the efficacy of the algorithm, the demand at each source and sink has been increased by 20%. Simulation was then performed on the same section for both with and without metering (Case 3 and Case 4 respectively). The MOEs in both the cases were recorded and compared (Table 4-1). As expected, the results show that the mainline delay has significantly reduced when ramps were controlled compared to the no control case. Although, the delay on ramps has increased significantly from case 3 to case 4, the combined mainline and ramp delay in case 4 is much smaller than in case 3. The above results indicate that the current algorithm is effective in

reducing the overall system delay for the demand set tried in this study, while more simulation runs need to be made with various sets of traffic demand before drawing conclusions.

(426) (427) (428) (429)
2500' 300' 1800' 300' 4600' 300' 900' 560' 740' 300'

(1362) (1355) (1039) (1358) (N17) (1361)
(430) (431)
600' 300' 1800' 300' 2900' 300' 1500' 400' 2400' 300'

(1365) (1364) (1901) (1904) (1905)

(432) (433) (435) (437)
1500' 400' 1000' 300' 2400' 300' 1400' 527' 1568' 350'

(1908) (1909) (1914) (1917) (1921) (1924)

(438) (439)
800' 340' 530' 530' 800' 300' 1370' 330' 1200' 300'

(1925) (1928) (1929) (1932) (11112)

(440) (441)
300' 1055' 1000' 600' 500' 300' 300' 300' 300' 300'

(11111) (1681) (1935) (1783) (1938) (1939) (1940)

(442) (443) (770)
300' 300' 450' 550' 550' 300' 700' 300' 2000' 300'

(1941) (1944) (1945) (1948) (3064) (3067)

(769) (768) (767) (766) (765)
3000' 300' 1900' 600' 2700' 400' 1600' 2000' 1050' 600'

(3058) (3061) (3052) (3055) (3047) (3017) (3050)

(755) (764) (763) (762)
900' 1700' 1750' 400' 2300' 300' 1000' 600' 900' 500'

(3051) (3043) (3046) (3036) (3016) (3039) (3040)

(760) (759) (222) (758)
1600' 300' 400' 1000' 3400' 1000' 900' 700' 800' 300'

(3030) (3033) (949) (946) (948) (947)
(756)

1200' 300' 2000'

(3020)

( ) Station Number

Fig 4-5 Geometry of 169 NB Test Section

26

Station 435

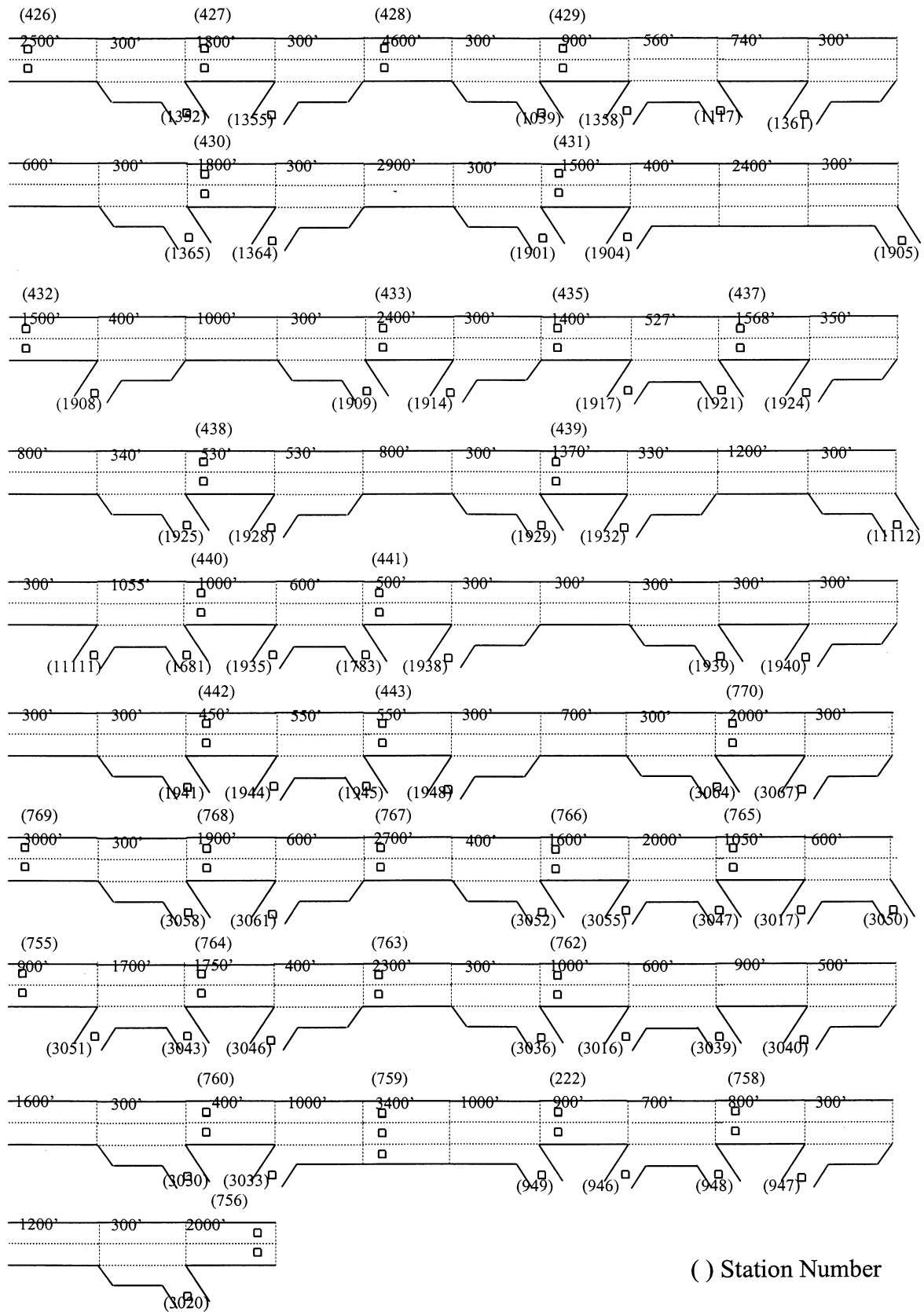**Station 435**
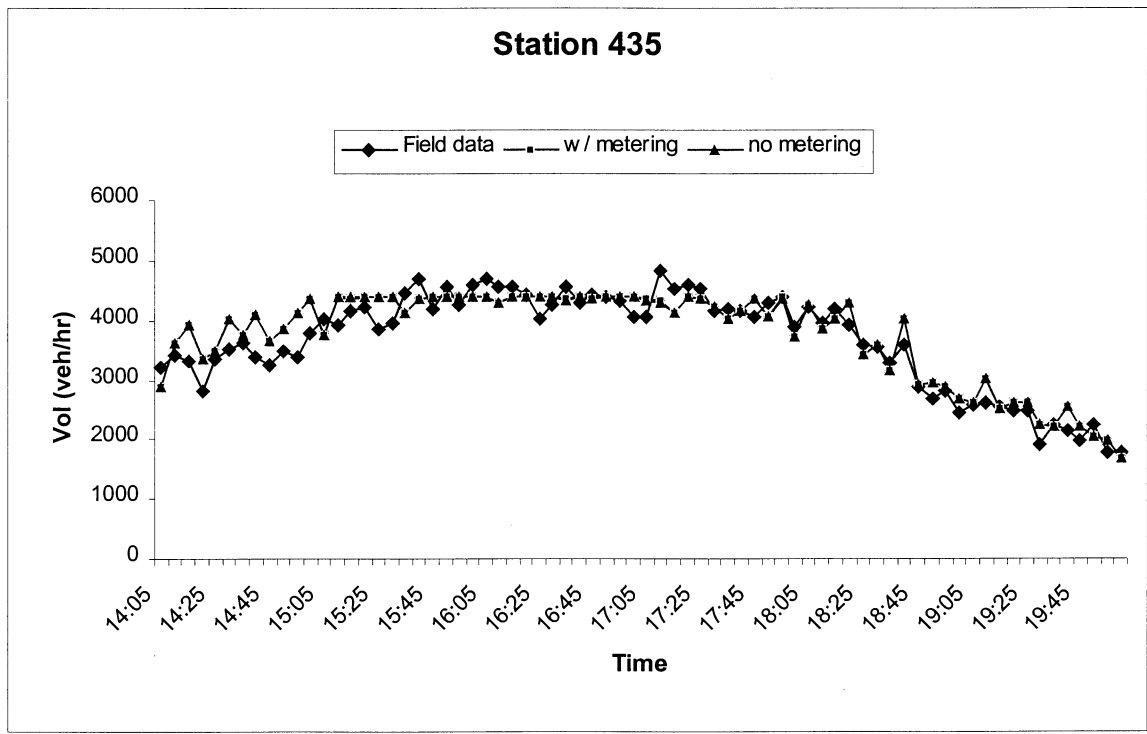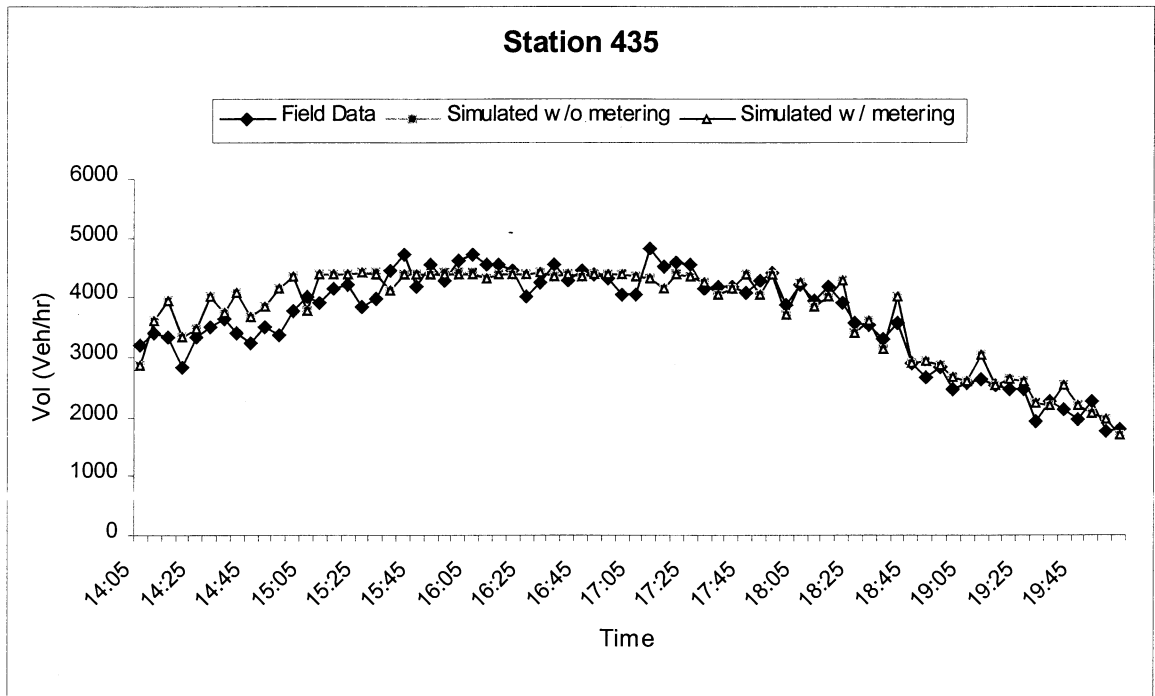
Figure 4-6 Model calibration results

Table 4-1 MOE values from different simulation runs conducted on a section of 169NB

		Case 1	Case 2	Case 3	Case 4
Cum Veh-miles	Mainline	326009.0	327916.0	330675.0	333554.0
	Ramp	21182.0	22702.0	25184.0	25633.0
	Total	347191.0	350618.0	355859.0	359187.0
Cum veh-hrs	Mainline	8719.0	7640.0	12852.0	8608.0
	Ramp	328.0	1241.0	824.0	1698.0
	Total	9047.0	8881.0	13676.0	10306.0
Cum delay (veh-hours)	Mainline	2097.1	1199.1	5917.2	1976.8
	Ramp	0.1	798.3	372.2	1176.8
	Total	2097.2	1997.4	6289.4	3153.6

Case 1: Current demand without metering control

Case 2: Current demand with metering

Case 3: 20% higher demand, but without metering control

Case 4: 20% higher demand, but with meter controlled

V. APPLICATION OF HOV LANE SIMULATION MODULE FOR I-94 CASE STUDY

V.1 Test section and model calibration

The diamond High Occupancy Vehicle (HOV) lane simulation module developed in the previous research was applied to a 10-mile (16km) section of the westbound I-94 freeway located in Minneapolis, Minnesota, to evaluate a set of hypothetical HOV lane scenarios. This test section has been selected in cooperation with the engineers at the Minnesota Department of Transportation as it is frequently congested during afternoon peak periods. Figure 5-1 shows the current geometry of the test section located between TH 47 and I-494 freeway. As indicated in this figure, this section of freeway has 11 entrance and 12 exit ramps with several lane-addition/drop segments. For calibration and testing of the base model, a set of 5-minute volume-occupancy measurements was collected from the loop detectors in the test section between 3:30p.m. and 6:30p.m. on April 9, 1998, when no incident or unusual event occurred. The calibration was performed by adjusting the capacity values of each segment until the differences between the measured and the simulated volume data at the mainline detector stations are within acceptable range. Figure 6 shows the comparison between simulated and field measured data for a typical mainline detector station located near the downstream of the test geometry. The mean percentage difference (MPD) and mean absolute error (MAE) between the measured and simulated volumes for a set of detector stations are presented in Table 1. These indices are calculated as

Mean Absolute Error (MAE) : $\displaystyle\sum \frac{|\text{Measured - Estimated}|_k}{N}$

Mean Percentage Difference (MPD) : $\displaystyle\frac{\sum \dfrac{|\text{Measured - Estimated}|_k}{Measured_k} * 100\%}{N}$

where, N = number of data points.

As can be seen from Figure 5-2, the simulation results followed the variations in traffic flow with reasonable accuracy. Further, as shown in Table 5-1, the mean percentage difference ranged from 5% to 10% for the three-hour simulation period.
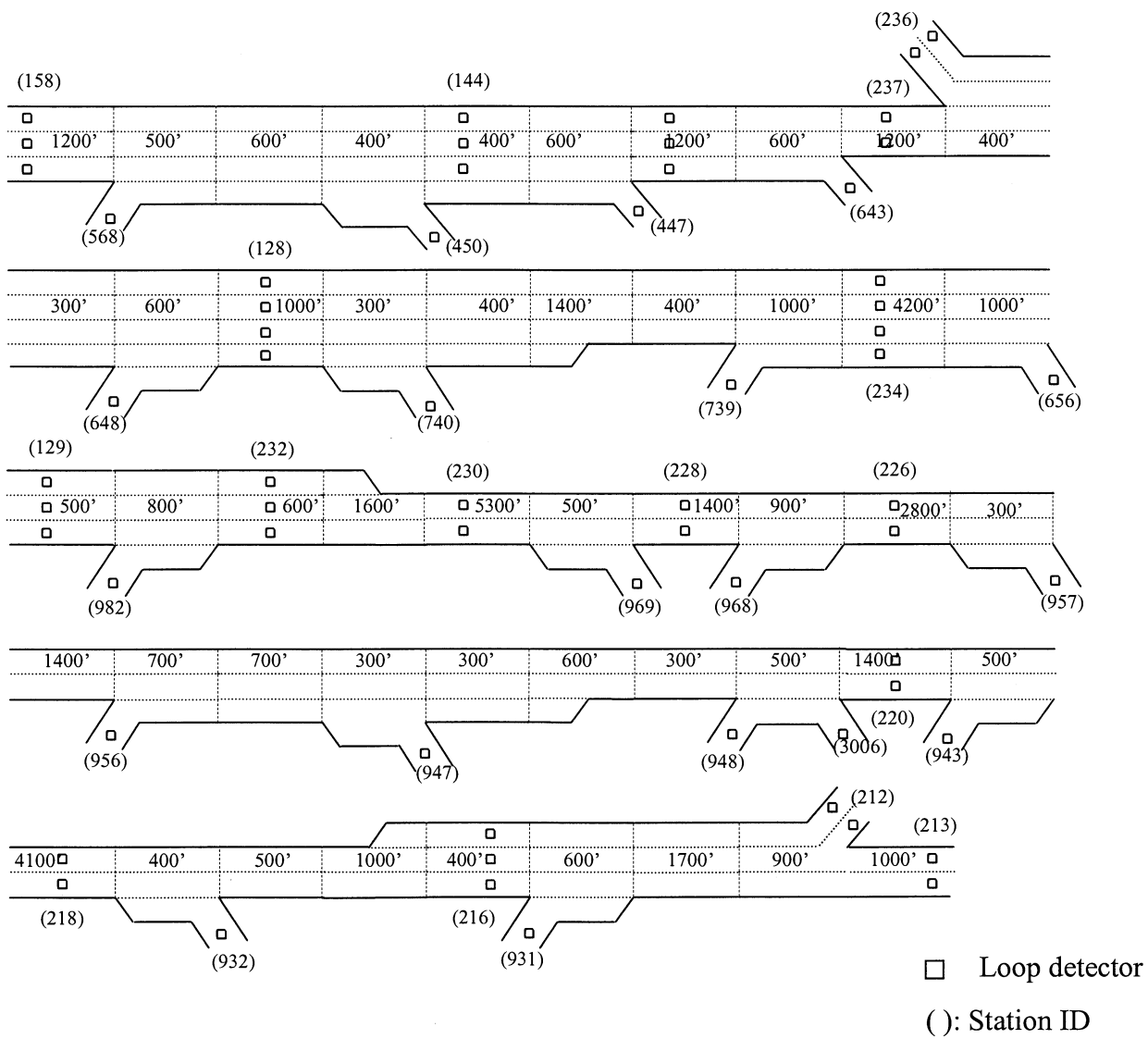
(236)

(158)   (144)   (237)

1200'   500'   600'   400'   400'   600'   1200'   600'   1200'   400'

(568)   (643)
          (128)   (450)   (447)

300'   600'   1000'   300'   400'   1400'   400'   1000'   4200'   1000'

(648)   (740)   (739)   (234)   (656)
(129)   (232)   (230)   (228)   (226)

500'   800'   600'   1600'   5300'   500'   1400'   900'   2800'   300'

(982)   (969)   (968)   (957)

1400'   700'   700'   300'   300'   600'   300'   500'   1400'   500'

(956)   (947)   (948)   (220)   (943)
                                                                (3006)
                                                           (212)
                                                                    (213)

4100'   400'   500'   1000'   400'   600'   1700'   900'   1000'

(218)   (216)
        (932)   (931)

□ Loop detector
( ): Station ID

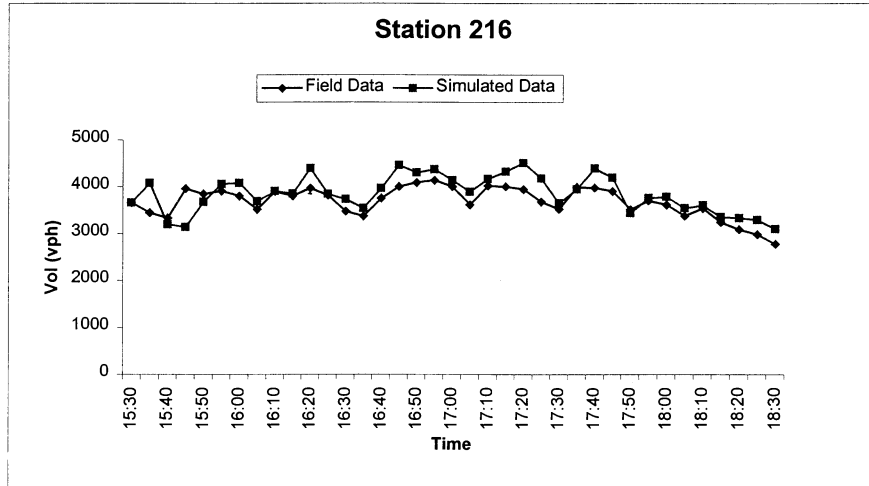Figure 5-1. Current Geometry of the I-94 Test Section

30

Figure 5-2. Comparison between observed and simulated volumes at detector station 216

Table 5-1. Volume estimation error at mainline detector stations

Station ID	MPD (%)	MAE (veh/hr)
143	4.45	193
144	4.66	250
216	7.40	284
220	7.46	287
226	8.17	315
232	9.94	415
234	7.28	385

V.2 Evaluation of alternative HOV lane strategies

As noted in Figure 5-1, the current geometry of the test section has several bottlenecks primarily caused by lane-drop sections. The preliminary study recommended the improvement of the current geometry by adding one lane to those lane-drop sections, so that there are at least three lanes throughout the section. Further analysis indicated that the proposed geometry would break down, i.e., congestion starts to build up (average speed in a segment dropped below 25mph), when the current demand is increased by 40%. In this study, the effectiveness of converting the left-most lane of the proposed geometry into a diamond HOV lane is evaluated with different proportions of the HOV lane traffic.

Figure 5-3 shows the proposed geometry and the diamond HOV lane location in the test section. The HOV demand scenarios evaluated in this study include:

Case 1: Current geometry with demand increased by 40%

Case 2: Same demand as in case 1, but with proposed geometry without HOV lane

Case 3: Same as case 2 with left-most lane designated as a HOV lane. HOV proportion
in total traffic demand = 5%.

Case 4: Same as case 3 with HOV demand proportion = 10%

Case 5: Same as case 3 with HOV demand proportion = 15%

Case 6: Same as case 3 with HOV demand proportion = 20%

It is assumed that the average number of people in a HOV is two and 5% of the current traffic consists of HOVs. Further, with the increase of the HOV proportion in total demand, the non-HOV traffic demand is also reduced accordingly.

Table 5-2 shows the estimated values of the measures of effectiveness (MOE) for each case resulting from a three-hour simulation. The delay is defined as the total vehicle-hours of the flow whose speed is less than the threshold speed value, which is determined by user. In this evaluation, 40 mph is used as the delay threshold speed. As expected, Case 3 with 5% of HOV proportion has the highest amount of non-HOV mainline delay, which drops to zero in Case 6 with 20% HOV proportion. Further, all four cases involving HOV lane have less amount of total vehicle hours and vehicle miles than those of Case 2 without a HOV lane. It can also be noted that in all four cases involving HOV lane, there is no delay in the HOV lane indicating that the HOV demand is still less than the capacity of HOV lane.
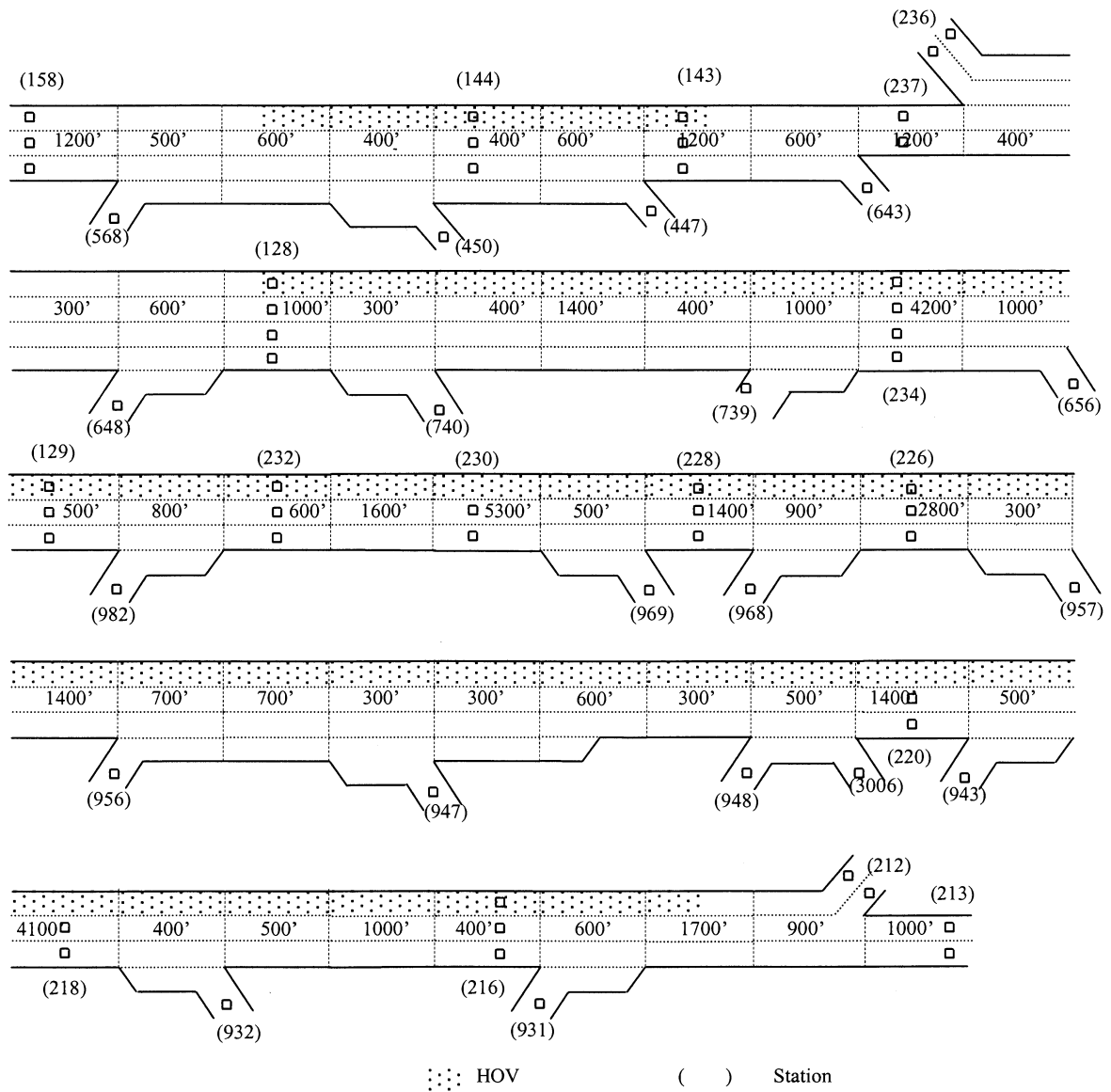
Figure 5-3. Proposed Geometry of the Test Section with HOV

33

Table 5-2. Estimated MOE values for each case

		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Total Vehicle-Hours	Mainline	6967	3078	2170	2222	2250	1661
	HOV lane	N/A	N/A	216	245	275	309
	Total	6967	3078	2386	2467	2525	1970
Total Vehicle-Miles	Mainline	124961	159244	108425	113314	117546	102027
	HOV lane	N/A	N/A	13271	15170	17051	18865
	Total	124961	159244	121696	128484	134597	120892
Total Delay (Vehicle-Hours)	Mainline	4202	123	308	273	223	0
	HOV lane	N/A	N/A	0.0	0.0	0.0	0.0
	Total	4202	123	308	273	223	0

VI. CONCLUSIONS

This report summarized the final results of the research project to support and test the freeway traffic simulation software developed at the University of Minnesota. For the technical support of traffic simulation, an experimental course was developed and implemented at the University of Minnesota for undergraduate students and traffic engineers. The course covered the fundamental theories in traffic flow modeling and simulation. Further, a set of metering case studies was conducted as class projects using the freeway simulation software supported in this research. To facilitate the application of the simulation software, an on-line help manual was also developed and incorporated into the software.

The simulation software was tested in this research through two sets of case studies involving the HOV lane and ramp metering simulation modules. The HOV lane case study used a section of the I-94 freeway and evaluated the performance of alternative HOV lane strategies with different sets of demand and HOV proportions. The ramp metering case study compared the performance of the current Mn/DOT metering policy with that of no-metering option for a 16 mile section of the northbound 169 freeway with increased demand. The results from these case studies, described in detail in this report, indicate that the simulation software can be applicable in evaluating alternative design and operational strategies for a given set of demand.

Future research needs include continuous improvement of the traffic models in the simulation software. In particular, the collection of real HOV lane demand data, including HOV exit volume and the location of lane changing point, is desirable to calibrate the HOV lane simulation module. The availability of such data would significantly improve the modeling of the effects of weaving between HOVs and the mainline traffic flow at merging/diverging points. The reduction of the capacity in HOV lanes when there is substantial speed difference between HOV and normal lanes also needs to be studied. Finally, freeway simulation needs to be expanded to include adjacent arterial streets, so that the effects of freeway operational policies can be evaluated on a corridor basis.

BIBLIOGRAPHY

Kwon, Eil, Michalopoulos, Panos, et. al. Enhancements of the KRONOS simulation package for geometric design, planning, operations and traffic management in freeway networks/corridors, Phase II, Final Report prepared for Minnesota Department of Transportation, University of Minnesota, 1995.

Lax, P. Weak solution of non-linear hyperbolic equation and their numerical computations, Comm. Pure. Appl. Math. 7, pp. 159-193, 1954.

Lau, Rich, Minnesota Traffic Responsive ramp metering algorithm, Internal documentation, 1997.

Borland International Inc., Boralnd Delphi for Windows 95 and Windows NT, version 2.0, Borland International Inc. 1996.

APPENDIX A: Syllabus for Technical Course

CE 5097

ADVANCED TRANSPORTATION MANAGEMENT SYSTEMS I

Fall 1998

Syllabus

Meeting place: Classroom, ITS laboratory, Center for Transportation Studies
Meeting time: MW: 16:40 – 18:30
Text: Handout
Reference: Transportation Engineering Journals (Transportation Research Record,
        Transportation Research, Journal of Transportation Engineering)
        Traffic Engineering, 2nd Edition, by Roger Roess, et al.
        Traffic Operations, by Carlos Daganzo
        Traffic and Highway Engineering, by Garber and Hoel
Instructor: Eil Kwon, kwonx001@tc.umn.edu
Guest lecturers: Glen Carlson, Rich Lau and John Biennick
        (Traffic Management Center, MnDOT)
Office: 213 Transportation and Safety Building
Phone: 625-1371, (fax: 625-6381)
Office Hours: M, W after class or by appointment

Course overview: This course, the first in the series of advanced transportation management
        systems, will address practical issues with current freeway traffic
        management and operations. Specific focus will be on the basic concepts/
        state-of-the-art strategies on ramp metering and application of traffic
        simulation for addressing freeway management issues. Current Twin Cities'
        ramp metering system will be used as an example system and its
        algorithm/current operational issues will be discussed. Further, a
        macroscopic traffic simulation software, developed at the University of
        Minnesota, will be introduced and used as a tool to evaluate and design
        alternative management strategies. Each student is required to conduct a
        class project that addresses at least one issue in current freeway traffic
        management.

Grading: Test on traffic flow concepts: 30%
        Individual class project (Final report :10-15 pages): 60%
- Problem identification and background study (include review of at least 3 papers on selected topic) : 20%
- Formulation of research objectives and development of solution approaches: 20%
- Results with proposed approaches and conclusions: 20%

        Interim reports on class project and in-class exercises, as assigned: 10%