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Final Report

Signal Operations Research Laboratory For Development and Testing of Advanced Control Strategies, Phase II

MINNESOTA DEPARTMENT OF TRANSPORTATION

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16. Abstract (Limit: 200 words)

The corridor simulation environment with the capability of modeling various types of traffic control strategies as the external control modules is of critical importance in developing and improving corridor management strategies. In this research, a microscopic network simulation model, Vissim, is used to develop such an environment, where the new stratified Mn/DOT metering algorithm was simulated using the 169 freeway and its performance was compared with those of the fixed-metering method. Based on the analysis results, an alternative approach to determine the minimum metering rate for each entrance ramp was developed and coded. Further, an adaptive approach to automatically coordinate a freeway meter with the adjacent intersection signal is also developed and evaluated using the corridor simulation environment. The evaluation results with a sample network consisting of one intersection and one entrance ramp show a clear advantage of the proposed method in reducing the overall delay at the ramp-intersection area, while producing higher or compatible total vehicle-miles compared with the conventional intersection-control methods, i.e., pre-timed and actuated, without employing ramp metering. The corridor evaluation environment developed in this study can be used for future studies including the continuous enhancement of the stratified metering algorithm to take advantage of the maximum allowable waiting time, automatic identification of the most effective metering strategy depending on prevailing traffic conditions, and extension of the adaptive coordination method to multiple intersections adjacent to a freeway entrance ramp.

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SIGNAL OPERATIONS RESEARCH LABORATORY FOR DEVELOPMENT AND TESTING OF ADVANCED CONTROL STRATEGIES, PHASE II

Final Report
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Executive Summary

Developing robust operational strategies that can optimize traffic performance in a given network is of critical importance in managing congestion and improving reliability of traffic systems. Such a development requires a realistic evaluation environment where various types of operational strategies can be directly implemented into actual controllers and simulated under different traffic and geometric conditions, so that the robustness and operational feasibility of new traffic control methods can be tested under the current hardware environment.

A previous phase of this research developed a hardware-in-loop simulation system that combined a 2070 traffic controller and a microscopic intersection simulator. In the resulting virtual intersection system, the 2070 controller was operated as a real field-controller with simulated detector data from the intersection simulator. In this research, the virtual intersection concept was extended to a freeway by developing a virtual corridor, which combines a microscopic network simulator, VISSIM, and a set of external control modules that can emulate different types of traffic control strategies in a freeway corridor. The network simulator adopted in this study models the detailed behavior of individual vehicles and allows a user to develop an external module that can determine the status of traffic signals in a simulated network at every simulation time interval. In particular, the VISSIM developer was able to provide a special version of the software for this research that required 0.1 second interactions between an external controller module and the main simulator. This 0.1 second feature was crucial for modeling the Minnesota ramp metering algorithm, which changes the red time of every meter on a 0.1 second interval.

Using the virtual corridor environment, the new stratified ramp-metering algorithm, which has been developed and implemented by the engineers at the Traffic Management Center, Minnesota Department of Transportation, was modeled and evaluated. First, the qualitative features of the VISSIM simulator were studied and the framework for on/off-line virtual controller modules was developed. Next, the new stratified metering algorithm was coded into an external controller module and simulated using a real freeway as the sample site. Specifically, a 16-mile section of northbound Highway 169 was used as a test site and modeled into the VISSIM simulator with the real geometry data. The simulation model parameters were calibrated with two days of real traffic data collected from the same test site. It needs to be noted that the evaluation of the new stratified metering algorithm required substantially more time and effort than initially planned, because the original plan was to

model the simpler zone-based metering algorithm, which was implemented before the stratified algorithm. The simulation results of the new metering algorithm were compared with those of the fixed metering cases under normal traffic conditions. The analysis results indicate that the new metering algorithm was effective in keeping the ramp waiting time under the pre-determined threshold values for all the meters in a test section. Further, the new algorithm resulted in slightly more restrictive control than the fixed metering cases by inducing longer ramp travel times at most entrance ramps. This produced some improvement of the mainline speeds over the fixed metering cases (that is, the speed levels were higher with less fluctuation through time. It was also noted that the ramp travel time that resulted from the new algorithm was substantially shorter than the pre-set values (4 minutes for normal ramps and 2 minutes for freeway-to-freeway ramps) indicating a possibility for more aggressive management of ramp queues within the pre-set waiting time limitations. To address the above issue, this study proposed an alternative approach to determining the minimum metering rate for each ramp and the source code for the alternative minimum-rate algorithm was also developed. It needs to be pointed out that the stratified metering algorithm evaluated in this study was its very early version, which has been continuously improved since its inception.

Finally an adaptive approach for coordinating an entrance ramp meter with an adjacent intersection signal was developed and evaluated using the virtual corridor environment. The main goal of the adaptive coordination algorithm developed in this study is to achieve a balanced operation between freeway and arterial flows by employing a measurement-based, direct-control scheme, as opposed to the conventional optimal-control approach based on predicted demand with hierarchical optimization. The adaptive control logic was coded into an external controller module that consists of the metering and intersection sub-modules. The metering sub-module continuously adapts its control rule to the ever-changing traffic conditions on the freeway, while the intersection sub-module explicitly reflects the traffic conditions at an entrance ramp as well as at intersection approaches to determine signal phases. For an example evaluation of the proposed adaptive coordination approach, a real-network consisting of one intersection and one entrance ramp was modeled with the virtual corridor and the performance of the proposed method was compared to that of the conventional no-coordination approaches, which adopt conventional intersection-control methods, i.e., pre-timed or actuated, without employing metering. The evaluation results show a clear advantage of the proposed method in reducing the overall delay at the ramp-intersection area, while producing higher or compatible total vehicle-miles than the no-coordination methods.

As described above, this research has demonstrated the capabilities of the virtual corridor in modeling various types of corridor management strategies and evaluating their performance under simulated environment. The list of subsequent studies recommended with the proposed corridor evaluation environment includes 1) Enhancement of the new stratified algorithm by taking advantage of the maximum allowable waiting time at entrance ramps, 2) Automatic identification of effective metering methods depending on the prevailing traffic patterns, 3) Incorporation of the adaptive coordination method into system-wide stratified metering, 4) Extension of the adaptive coordination approach to the adjacent traffic signals in a same network, 5) Estimation of the effects of driver information systems (for example, VMS) on corridor traffic patterns, and 6) Continuous development of freeway-arterial performance quantification/evaluation methodologies.

1. Introduction

1.1 Background and Research Objectives

A virtual network environment where new advanced control concepts can be refined and tested with field controllers prior to field implementation is of critical importance in developing an efficient network control strategy that has real-time operational capability. Previous phase of this research has developed a pseudo real-time testing environment for a single intersection by integrating an advanced traffic controller and the newly developed microscopic traffic simulator. The communication between the simulator and the controller is performed through the signal converter also developed in the previous phase. The resulting virtual intersection system was used to evaluate an adaptive intersection control strategy, which was directly implemented into a 2070 controller.

In this research, the virtual intersection concept is expanded to a freeway corridor with a microscopic network simulator, Vissim. The ultimate goal of this study is to develop robust and efficient strategies that can automatically coordinate freeway ramp meters and intersection signals in a corridor, so that the existing capacity of a given network can be used as much as possible. The specific objectives of the current phase include

- Development of an evaluation environment for corridor control strategies using a microscopic network simulation model and virtual controllers,
- Modeling the new Minnesota stratified zone metering algorithm with the virtual controller and evaluation of its performance to aid the traffic engineers at the Minnesota Department of Transportation (Mn/DOT) in enhancing the algorithm,
- Development and evaluation of a new adaptive coordination strategy for a ramp-intersection area using the corridor testing environment.

The Vissim, selected as the main simulator for this study, models the behavior of individual vehicles in a network in detail and allows a user to develop external controller modules for modeling various types of control strategies. In particular, a special version of the Vissim was provided to the research team by the developer, who modified the original version to be able to make the interaction between the main simulation module and an external controller module happen every 0.1 second. This feature is crucial in modeling the new Minnesota metering algorithm that changes the metering rates every 0.1 second.

1.2 Report Organization

Chapter 2 reviews the microscopic simulation model selected for this research and discusses the results from qualitative testing. The basic framework for the virtual controllers, on/off-line, is also developed in Chapter 2. The newly developed Minnesota metering algorithm is then modeled in Chapter 3 and simulated under the virtual corridor environment using the 169 freeway as the sample section. Chapter 3 also includes the simulation results of the new metering algorithm compared with those of the fixed metering. Chapter 4 reviews the existing literature for coordinated control methods and develops a new adaptive coordinated strategy for a ramp-intersection area based on direct control approach. The detailed procedure and evaluation results of the adaptive strategy with the simulation model are also included in Chapter 4. Finally Chapter 5 contains conclusions and future research needs.

2. Development of a Testing Environment for Freeway Corridor Control Strategies

2.1 Overview of Selected Network Simulation Model: VISSIM

Developing a testing environment for corridor control strategies requires a microscopic network simulation model that can 1) realistically model traffic behavior responding to different types of traffic control strategies and 2) allow flexible implementation of various types of traffic control strategies. The latter requirement is of critical importance for this research, whose ultimate goal is to develop realistic corridor-wide traffic management strategies. In this research, the VISSIM microscopic network simulator was selected as the simulation model for its flexible structure and the developer's willingness to provide a special version for this study to make the interaction between an external control module and the VISSIM main simulation module happen every 0.1 second, while the standard version of VISSIM only allows 1 second interaction. This capability was very critical for this study, since the unit time of the red time intervals for all the freeway ramp meters in the Minnesota metro area is 0.1 second. The rest of this section includes the brief overview of the VISSIM model based on the description of its manual (1).

VISSIM is a stochastic, time-scan and behavior based simulation tool designed to model complex urban and public transit operations under various geometric conditions, such as interchanges and roundabouts, etc. It consists of two main modules: Traffic Simulator and Signal State Generator. The traffic simulator contains a psycho-physical car following model for longitudinal vehicle movement and a rule based algorithm for lateral movements. . The model is based on the Wiedermann car following model, which assumes that a driver can be in one of four driving modes:

- Free driving- No influence of the preceding vehicle is observable. In this mode the driver seeks to maintain a certain speed, his individually desired speed.
- Approaching- The process of adapting the driver's own speed to the lower speed of a preceding vehicle.
- Following- The driver follows the preceding car without any conscious acceleration or deceleration. He keeps a safe distance without any constant acceleration or deceleration.
- Braking- The application of medium to high deceleration rates if the distance falls below the desired safety distance.

The acceleration for each mode is described as a function of speed, speed difference, distance and the individual characteristics of driver and vehicle. In case of multi-lane roads a hierarchical rule set is used to model lane changes. For the implementation of the model, time is incremented in small discrete steps. The time step influences the resulting driver behavior. The simulator is capable of simulating up to ten times per second. The signal state generator is a software module that can act in response to detector information received from the simulator. Figure 3.1.1 shows the simplified structure of the VISSIM simulation model.

The input required by VISSIM is comprised of two types of data: static data and dynamic data. Static data is the data that remains unchanged during the simulation and dynamic data is data containing all information about the simulated traffic. Static data represents the roadway infrastructure.

Static data includes:

- Links with start and end points as well as optional intermediate points; links are directional road segments with a set number of lanes
- Connectors between links to replicate turning possibilities.
- Position of signal heads/ stop lines including a reference to the associated signal phase.
- Position and length of detectors
- Location and length of public transit stops

Dynamic data is only to be specified for traffic simulation applications. It includes the following information:

- Traffic volumes including truck percentages for links entering the network
- Location of route decision points with routes (link sequences to be followed) differentiated by time and vehicle classification.
- Priority rules (right-of-way) to model unsignalised intersections or permissive left turns
- Location of stop signs
- Public transport routing, departure times and dwell times

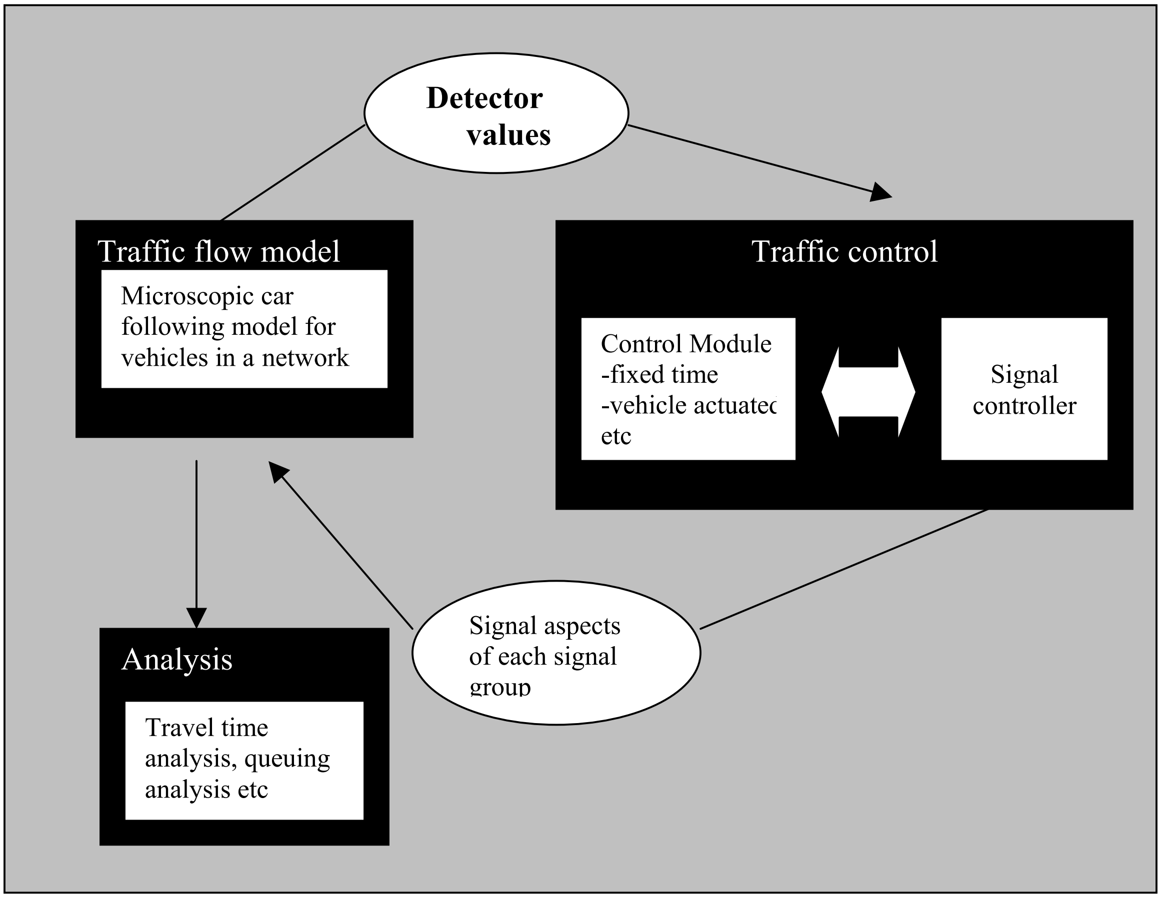


Figure 2.1.1. Simplified structure of VISSIM

- Vehicle parameters (length, max speed, max acceleration etc)
- Turning movement percentages
- Reduced, desired speed zones.
- Signal control procedure and signal phasing

VISSIM provides a variety of output files that can be used to compute different measure of effectiveness (MOEs). Some of the typical outputs include speeds, volume, occupancy and density values. Further, VISSIM also generates information about travel time and delay between any two connected points on a road network. One big advantage for VISSIM compared to other commercial microscopic simulators lies in its ability to provide online graphical evaluations like signal changes and detector occupancies.

2.2 Qualitative Testing of VISSIM

VISSIM has the ability to model complicated geometries. It can model rural, urban as well as interstates. The major differentiating factor between VISSIM and other simulators is its use of links and connectors to represent road networks rather than links and nodes. This allows one to build smooth curves at intersections and roundabouts. To build an accurate road network a detailed background map that replicates the existing infrastructures to some scale should be used as a base. Typically these can be background files are bitmaps generated from aerial photographs or CAD files.

For the qualitative testing of the VISSIM functionalities, an example network is coded into VISSIM in this section. The aerial photos of the 7 county Twin Cities (Minneapolis and St. Paul) Metropolitan area were used to generate the background maps for coding the sample road network in VISSIM. These aerial photos, available in a CD, are black and white Digital Ortho-photo Quarter-quadrangles (DOQs), 3.75' x 3.75', covering the 7 county Twin Cities (Minneapolis and St. Paul) Metropolitan Area in Minnesota. Each CD-ROM contains up to 4 quarter-quadrangles of a USGS 7.5 minute quadrangle. The ortho-photos are in UTM, Zone 15 and NAD83 projection. Each image is approximately 115 MB, with a 0.6 meter image pixel, and available in TIFF format from the Metro Council. These ortho-photos follow the USGS DOQ specifications except for the file format and the scan resolution (pixel size is .6m rather than 1 meter). The original imagery was collected at 20,000 ft. and centered on USGS quarter-quads.

The scale for the Aerial photo was obtained using the GIS package ArcView. After loading the theme into ArcView, the projection properties have to be set as shown in Figure 2.2.1:

Horizontal Coordinate Scheme	UTM
Horizontal Datum	NAD83
UTM zone Number	15
Horizontal Units	Meters

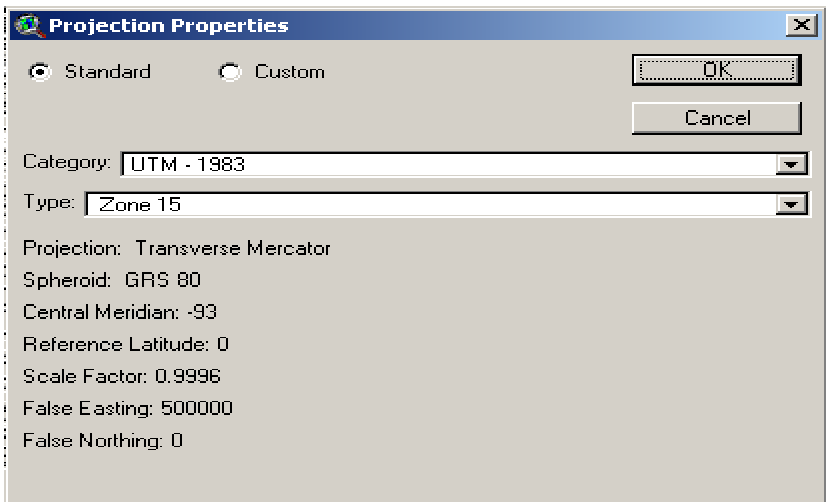


Figure 2.2.1 Projection properties for aerial photos

Once the properties of the theme are set, the scale of the background map required for VISSIM can be obtained by drawing a line segment on the theme in ArcView. The required portion of the background map can be cropped and exported as a Bitmap file for use in VISSIM. Figure 2.2.2 shows the ortho-photo including the University of Minnesota campus network. The line in the photo indicates a length of 1000.96 meters. This is used as scale in VISSIM. In this study, using the aerial photos of the Twin Cities metro area, several example VISSIM networks were created to test the network editing features of the VISSIM. Further, the qualitative testing of the controller functions was also conducted. The results of these testing were used to develop off-line external controller modules described in the next section.

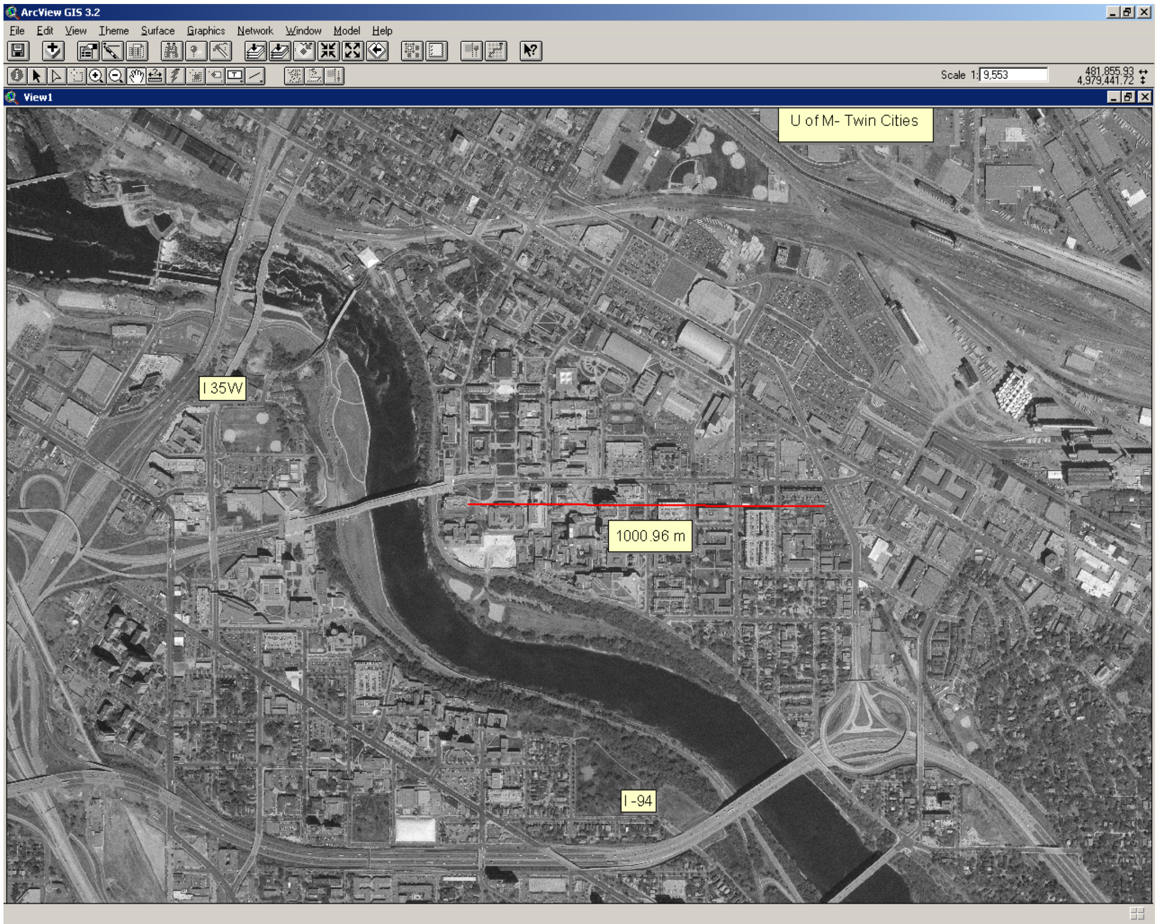


Figure 2.2.2: U of M Twin Cities area in ArcView

2.3 Development of Off-line Controller Module and Integration with VISSIM for Off-line Corridor Testing Environment

In VISSIM signal control can be done using either the built-in, fixed time controller or an external signal state generator that needs to be written in C following specific format and functions offered by VISSIM. The external signal control module interacts with VISSIM every simulation second. It is done through a form of inter-process communication called *Dynamic Data Exchange* (DDE). DDE is a feature of the Windows operating system that allows two programs to share data or send commands directly to each other. It uses shared memory to exchange data between applications. Applications can use DDE for one-time data transfer or for ongoing exchanges and updating of data. DDE can be thought of as an automated version of the Copy and Paste method. In most cases, one application provides some form of data to another application. The application that is the source of the data is called the "server" and the application that is receiving the data is called the "client". Thus, a DDE conversation is the interaction between client and server applications. For every simulation time step, VISSIM sends in the detector data to the control module. During this period VISSIM acts as the server and the control module as the client. The control module generates the signals and these are then transferred to VISSIM. In this period the control module is the server and VISSIM is the client.

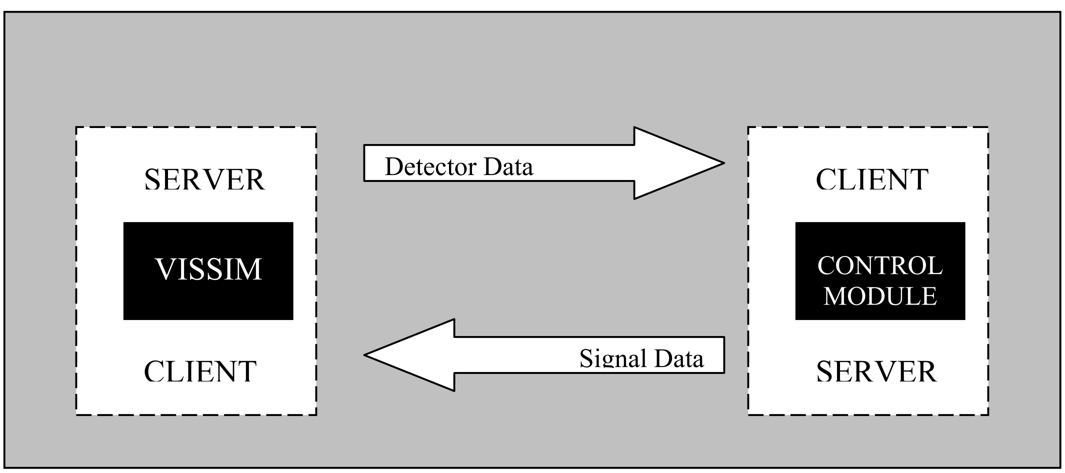


Figure 2.3.1 Client/Server relationship between VISSIM and external control module

The disadvantage of using this type of client/server mechanism for the signal control procedure is the potential to overload the model with DDE links causing the model to run more slowly or become dysfunctional.

In this section, two virtual controllers were developed and integrated with VISSIM to test the features of the VISSIM and also to be used as the bench mark controllers for comparing the performance of the new adaptive control algorithm that would be developed in the later part of this research. Further, the knowledge gained through this experimentation can be directly used to develop the external controller modules for the new adaptive controller as well as the new ramp metering algorithm. Specifically the commonly used fixed-time control and NEMA actuated control algorithms were coded in C language as the external virtual controllers. The results were later compared with built-in fixed time and NEMA control logics.

2.3.1 Fixed-time virtual controller

For fixed time control the actual intersection between Washington Avenue and Oak Street in the University of Minnesota campus has been coded into VISSIM. An external signal control procedure was developed for this and the phases of the signal heads were changed through DDE communication on a pre-timed basis. In this process the functions used internally by VISSIM are employed. Figures 2.3.2 and 2.3.3 show the sample intersection geometry and the types of signal phases used for pre-timed control. Figures 2.3.4 and 2.3.5 also show the implementation of fixed time control at an isolated intersection with a cycle period of 80 second. Each signal group has a green time of 20 seconds.

2.3.2 Actuated virtual controller

In actuated control, the controller determines the phase status for each approach every simulation second using the actuations from the detectors in a given network. For an isolated intersection, first a minimum green time is assigned for each phase and the green time for the current phase is increased by unit extension if the detectors corresponding to its signal groups are actuated. The unit extension is usually equal to the time that a vehicle takes to reach the signal at the speed at which it is traveling. This speed can be either fixed by designating the zone as a desired speed zone or can be varied. If the speed is not fixed, it can be determined using the

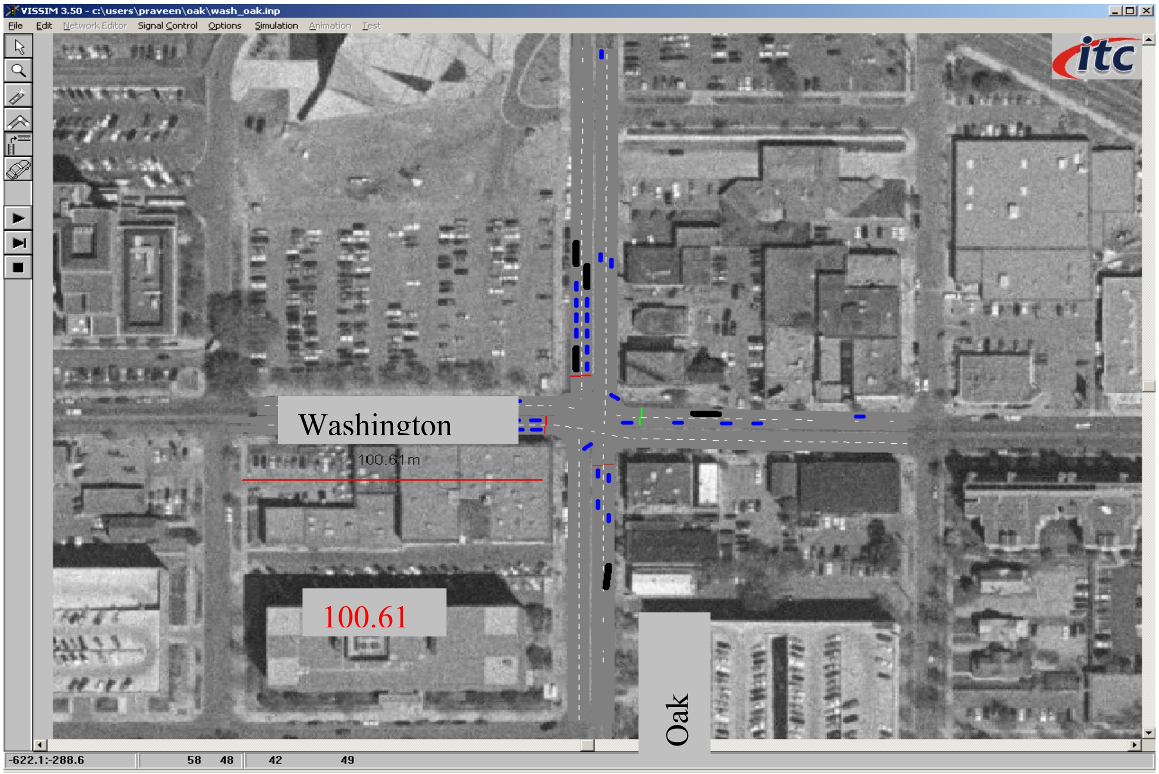


Figure 2.3.2 Sample Intersection used for Virtual Controller development

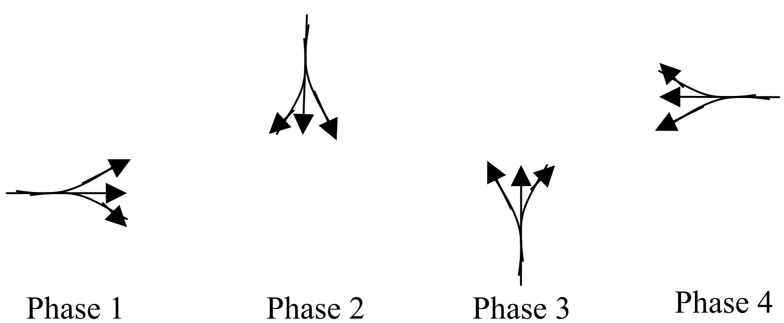


Figure 2.3.3 Phases for pre-timed intersection control

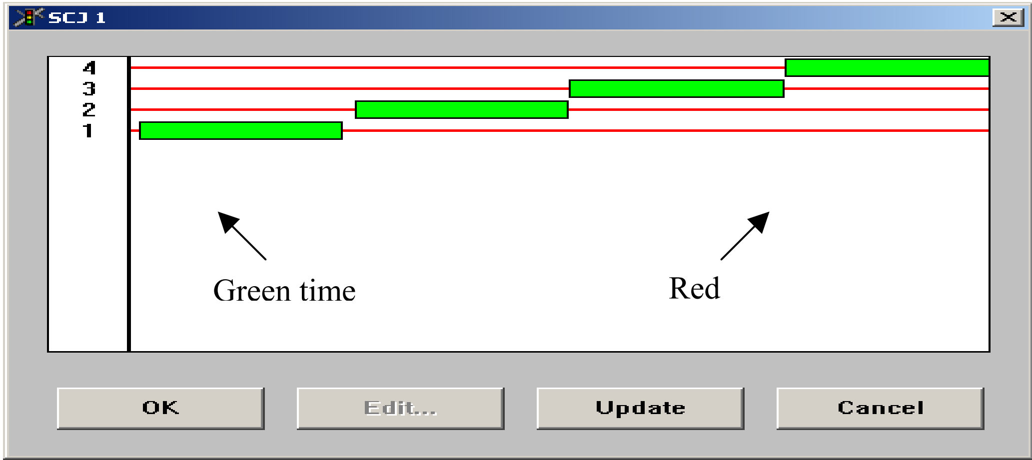


Figure 2.3.4 Signal control junction Settings

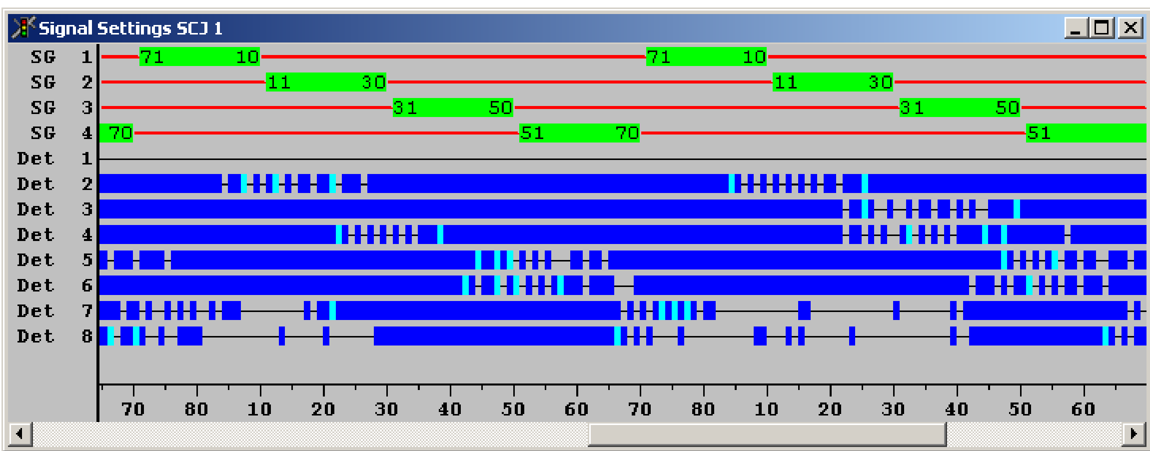


Figure 2.3.5 Signal phases and detector recordings for two cycle lengths with external module during test simulation

functions of the external control module, so that the unit extension time can be varied with the speed of a vehicle. The green time for a phase is terminated if the calculated green time surpasses the maximum green time or if there are no actuations during the allotted green time. Figure 2.3.6 illustrates the actuation-extension sequence of the common actuated-control logic.

Phase modeling for actuated control:

In VISSIM each lane has a separate signal head and any number of signal heads can be grouped together to form a signal group. At a given point of time all the signal heads in a signal group will display a same phase. The phasing at a signal junction will depend on the grouping of the signal heads. For the purpose of developing an example, external actuated controller module, a generalized intersection was developed with a phasing sequence as shown in figures 2.3.7 and 2.3.8. The advantage of working with signal groups is that the external program can be generalised and can be used to model any given combination of phases. This can be done by changing certain parameters in the input file. The input file, which can be manually edited, has certain required format shown in Figure 2.3.9.

Figure 2.3.10 shows the structure of the external actuated control module developed in this study. As indicated in the figure, it consists of five major functions, which are described as follows;

Actuation_Check: This function checks for the actuations on all the detectors belonging to the signal control junction every simulation second. It will call three other functions depending on the value of the variable localtime and the detectors which are actuated in the simulation second. If none of the detectors are actuated the control program ends for the simulation second. If localtime is greater than greentime (greentime expires), the function Group_generator is called, if a detector belonging to the current active phase is actuated and greentime has not expired then the function Green_time_calculation will be called and if a detector belonging to some other group is actuated then the function Update_detector_time is called.

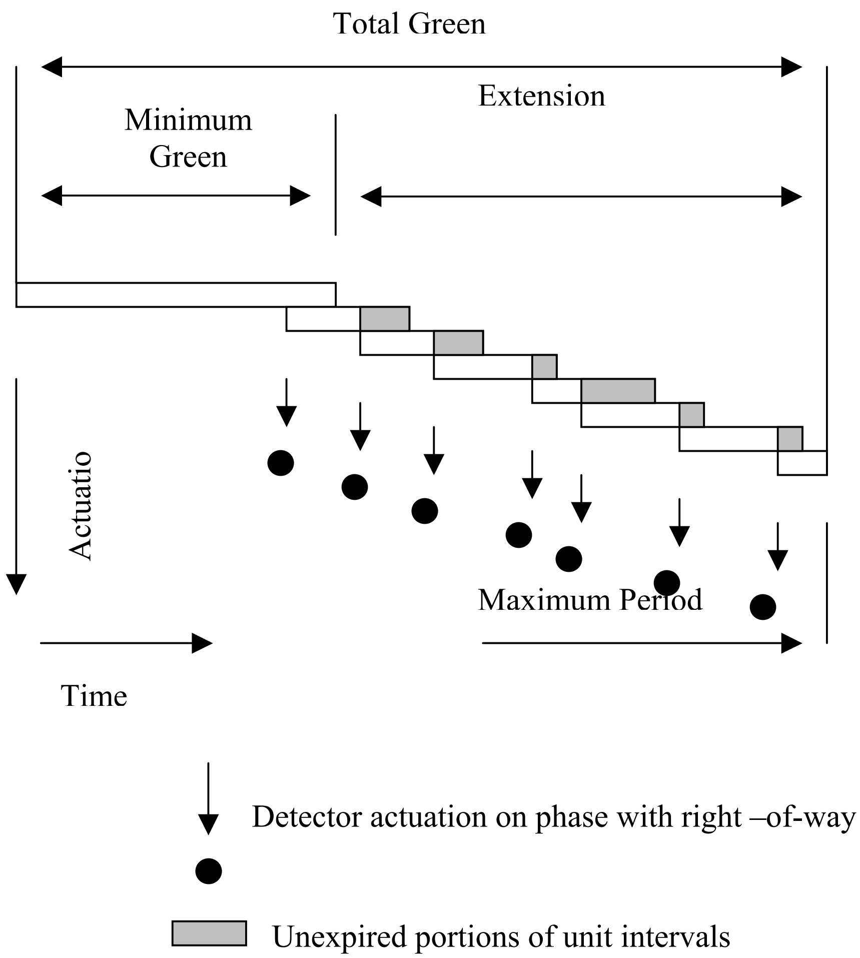


Figure 2.3.6 Implementation of Actuated control for an isolated intersection

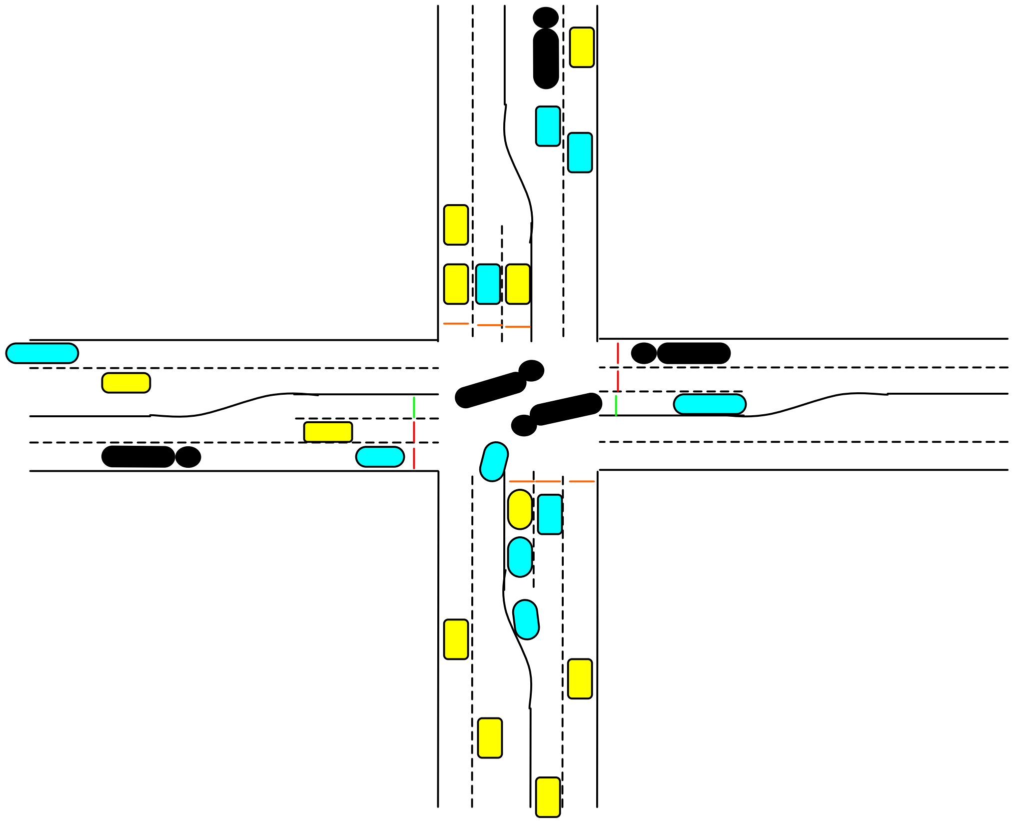


Figure 2.3.7 Sample Isolated signalised intersection with exclusive left turn lanes

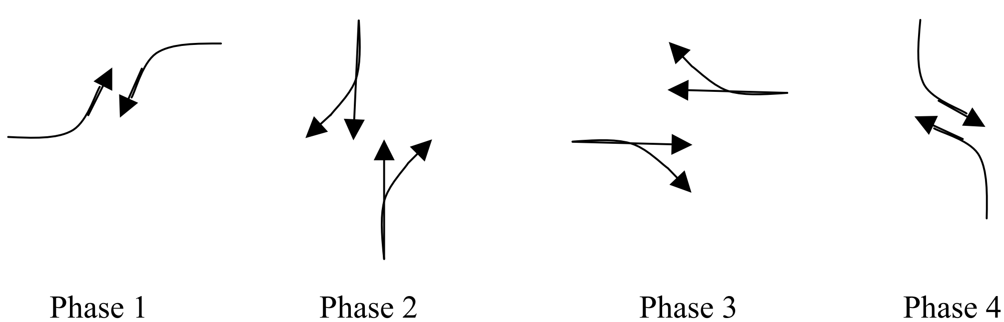


Figure 2.3.8 Phase combination for sample intersection with exclusive left turn lanes

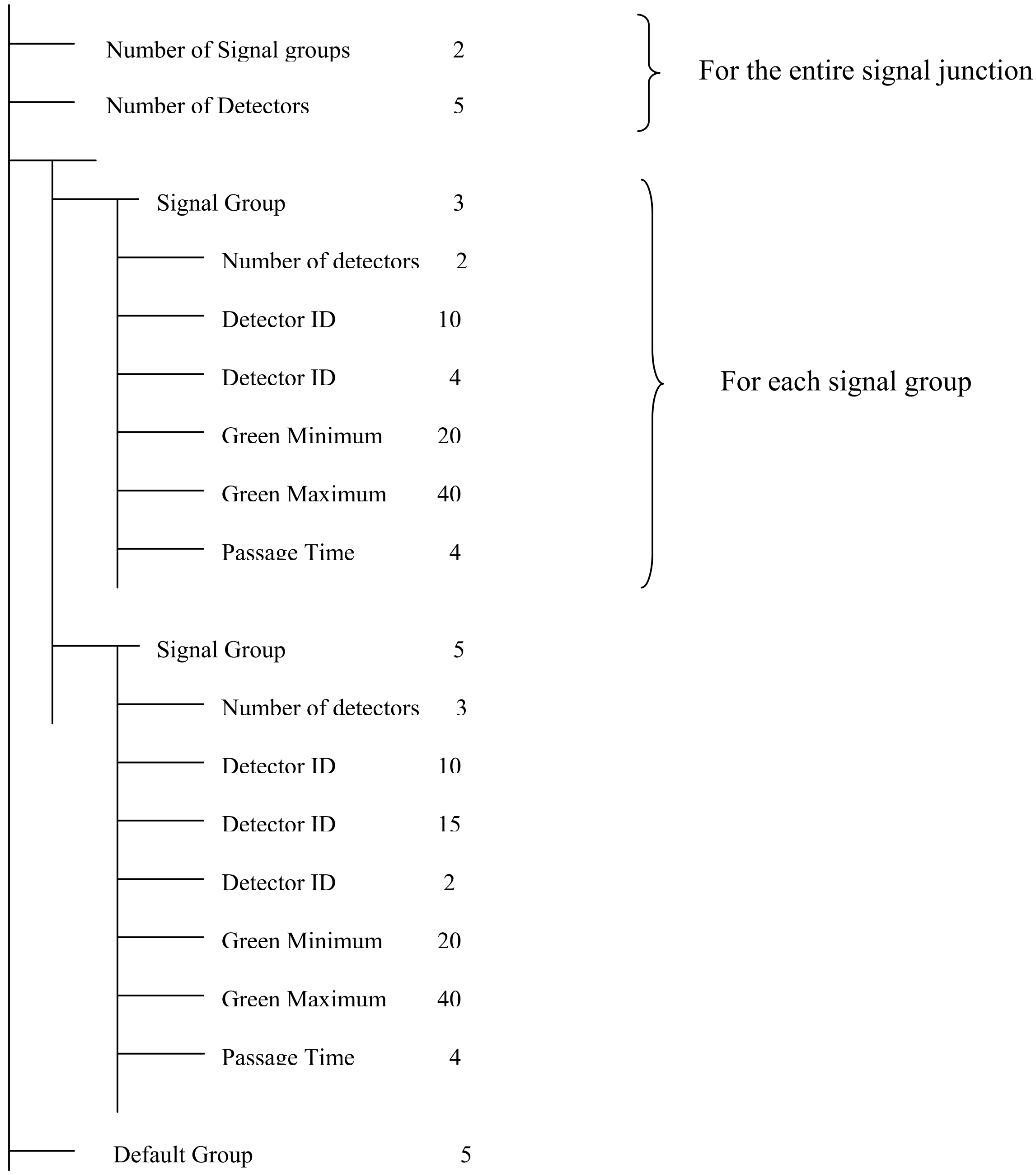


Figure 2.3.9 Input file format for external actuated control

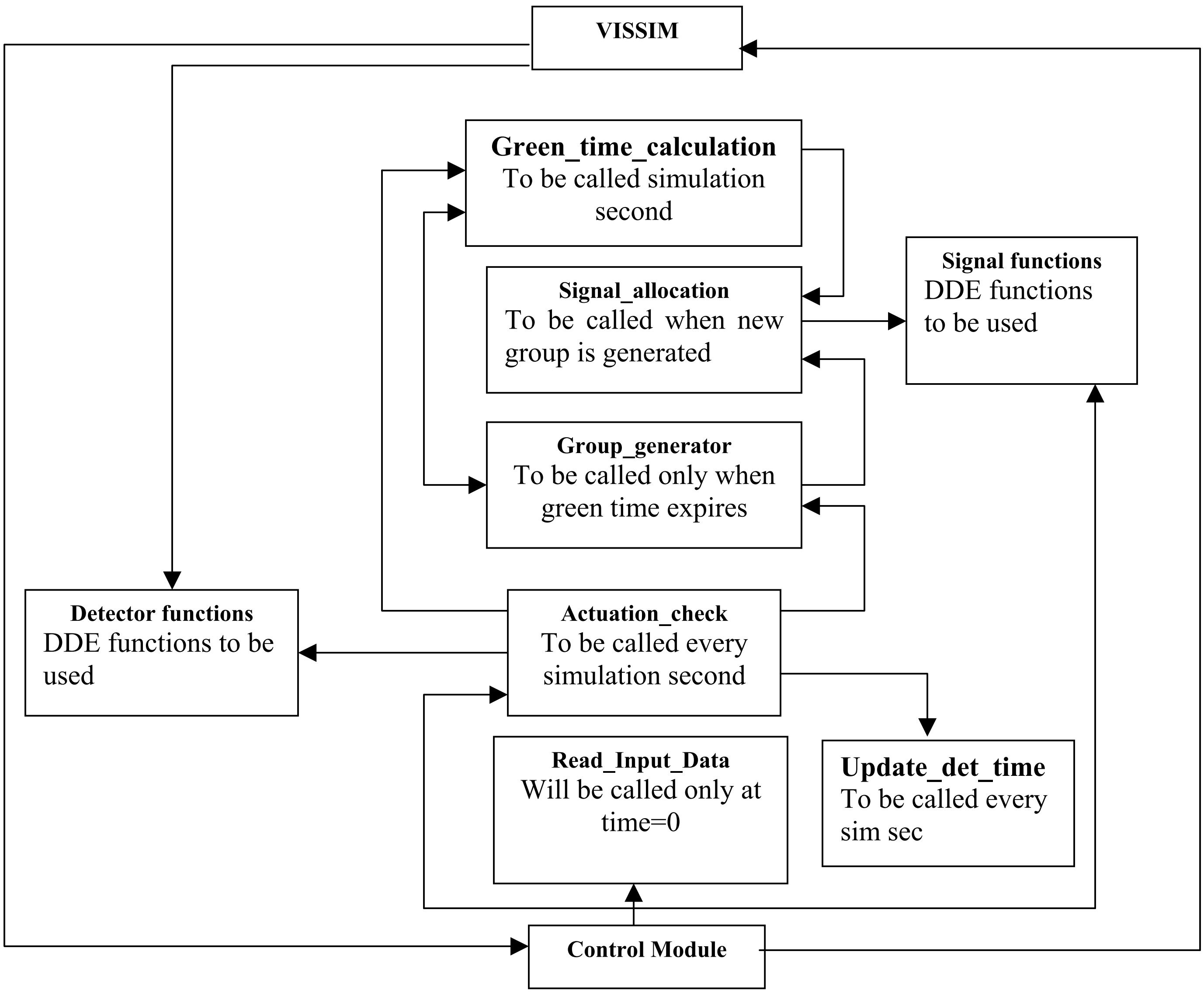


Figure 2.3.10 Structure of virtual Actuated controller module

Green_time_calculation: This function calculates the green time for the current running phase. For the first simulation second the green time will be the minimum green time of the first group that is to be given green as specified in the input file, after that the green time will be varied depending on the actuations of the detectors. The function is called only if the detectors of the signal group corresponding to the current active phase are actuated. If they are actuated the green time will be extended else it will be same as the last computed value. If the green time for a signal group expires, the green time for the next waiting phase will be equal to its minimum green time.

Update_detector_time: Function will be called only if any of the detectors not belonging to the current active phase are actuated. If a detector is actuated, then the time (simulation second) at which it was actuated is stored in a memory location. If the memory cell already contains a non-negative number it implies that an earlier actuation time has been stored for this detector and the value in the cell will not be updated, thus not disturbing the waiting calls order. The function also arranges all the detector actuated times in ascending order. In this way the next waiting phase will be the one corresponding to the first detector in this sorted list. Whenever a new group is generated the actuated times of the corresponding detectors are given a negative value and are pushed to the bottom of the sorted list.

Group_Generator: Whenever the green time expires for a certain phase the signal group has to be changed to the next waiting phase. The group generator takes the detector id from "update_detector_time" with the smallest actuated time stack arranged in ascending order and gives green time to the signal group corresponding to the detector id that it obtained. The green time allotted will be equal to the minimum green time specified by the user in the input file.

Signal_Allocation: This function allocates the signals (red, green) to all the signal groups in the signal control junction and will be called only if there is a change in the current signal group.

Performance Comparison between External actuated module and Built-in controller

In this section, the performance of the external actuated controller developed in this study was tested and compared with that of the built-in actuated controller of VISSIM. Figures 2.3.11 and

2.3.12 show the sample intersection used for testing and the phase definition of each signal group. For modeling an actuated control for this intersection with the built-in control module, the detectors on the non-exclusive left turn lanes for each approach should have the same number, whereas the external module will have different numbers. Thus, there will be eight different detector numbers for the built-in module and twelve for the external module. Table 2.3.1 shows the average green time comparison for all four signal groups resulting from a test simulation. As indicated in the table, the results from the external control module are very close to those from the built-in controller.

Table 2.3.1 Average green Time (seconds) for each signal group

Signal Group	3	4	5	10
Built-in	31.5	24.7	25.5	27.8
External	30.2	26.8	27.0	25.1

The flexibility provided by the external control program can be used to model any type of signalized intersection. For example a four-way intersection can be modeled as a T-intersection by equating the vehicle inputs on one of the approaches to zero. In such a case the signal heads for the approach with zero-vehicle input will always display red. For example by making the number of vehicles for approach 1 in figure 2.3.11 zero, we should expect to see that the average green times for the groups 10 and 4 to remain the same and those of groups 5 and 3 to reduce. The green time distributions for this case for the external control module are tabulated below:

Table 2.3.2 Average green time for a hypothetical T-intersection

Group	3	4	5	10
External	25.9	26.2	25.6	25.1

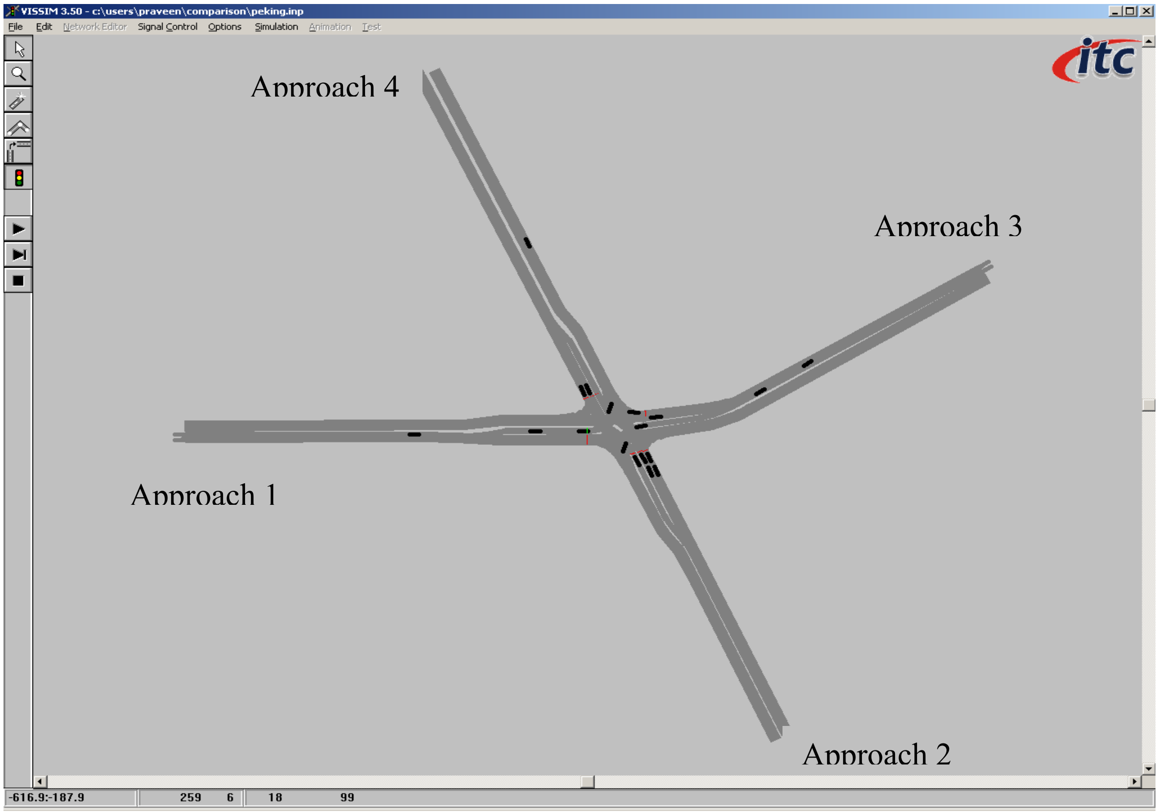


Figure 2.3.11 Sample intersection as modeled in VISSIM

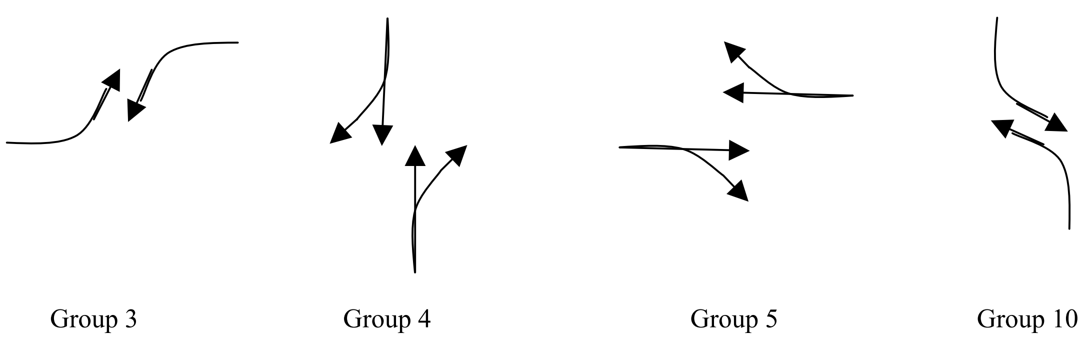


Figure 2.3.12 Phases modeled as groups

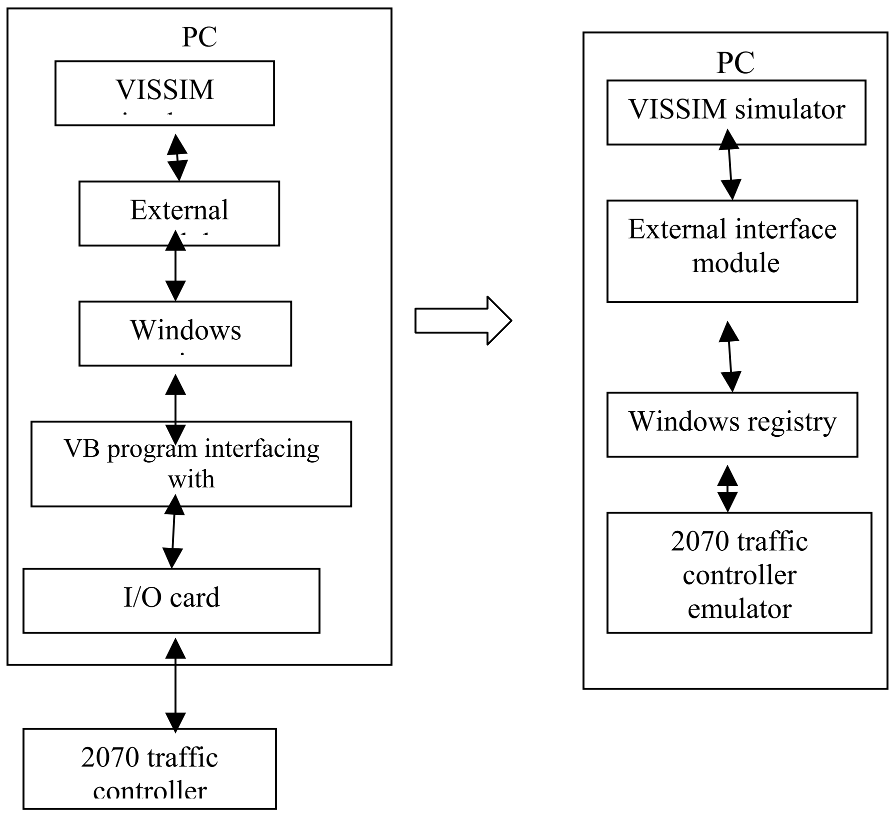
2.4 Development of On-line Virtual Controller Module and Integration with VISSIM for Pseudo Real-Time Testing Environment

2.4.1 Framework for Pseudo Real-time Testing Environment

Previous phase of this research developed a hardware-in-loop simulation system, where a real traffic controller is connected to a traffic simulator through an interface. While such a system allows direct coding of control algorithms onto the controller hardware, it requires the time-consuming embedded programming effort with the knowledge of special compiler and hardware-specific functions. In this research, a Visual Basic software was developed to emulate the functionalities of the 2070 traffic controller, so that coding/debugging of the control algorithms can be conducted as efficiently as possible. The resulting controller module can interact with the VISSIM network simulation model through the new interface software, which is also developed in this research. Figure 2.4.1 shows the simplified frameworks of both the hardware-in-loop simulation structure developed in the previous phase and the virtual controller-based pseudo real-time simulation developed in this research. As indicated in the figure, in the pseudo real-time simulation environment, the control emulator replaces the input/output card and the real controller hardware, while the interface structure remains same. As in the hardware-in-loop simulation case, the control emulator contains both specific control algorithms and data transmission module, which sends/receives the data through the Windows Registry used as the data sharing place between the control emulator and the VISSIM simulator. By using the Windows registry, it is possible to develop and run the emulator independently from the simulator, since the only common area between VISSIM and the emulator is the Windows registry.

2.4.2 Development of Virtual Controller Module

Figure 2.4.2 shows the detailed structure of the virtual controller module developed in this study with the Visual Basic language. As shown in the figure, the emulator consists of three main threads, i.e., timers, which play major roles. The first thread collects the simulated detector data from VISSIM. The second and third threads analyze and determine the status of traffic signal heads, i.e., ramp meter and intersection signal heads, following pre-stored control algorithms. For example, the intersection traffic signals are operated by FIXED, ACTUATED and ADAPTIVE algorithm modules, while ramp traffic signals are managed by



Hardware-In-Loop Simulation

Pseudo Real-Time Simulation with Virtual Controller

Figure 2.4.1 Framework of virtual controller-based pseudo real-time simulation

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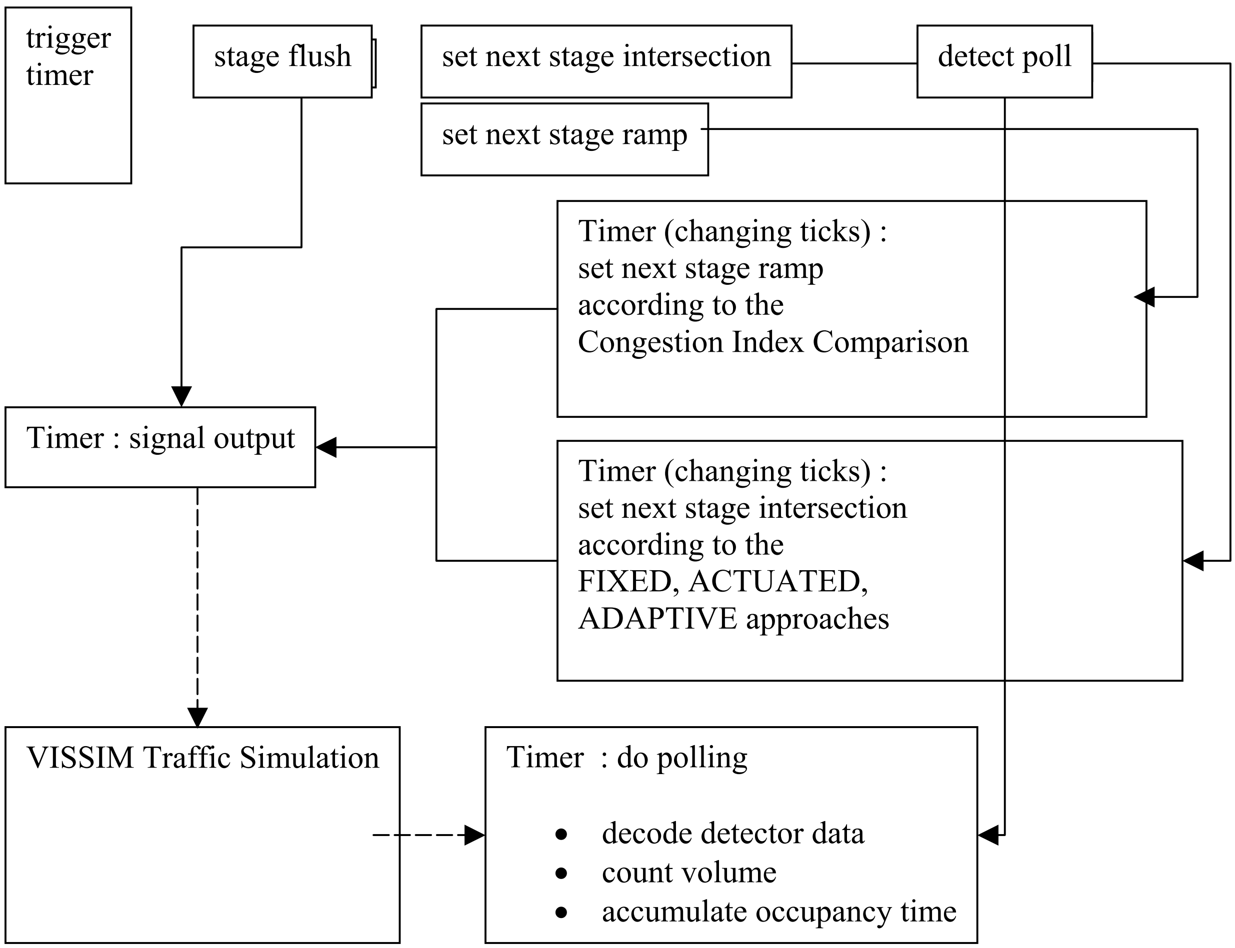


Figure 2.4.2 Structure of the controller emulator

NO_METERING, FIXED_METERING and NEW_METERING modules. The last thread sends traffic signal-head data to VISSIM, which continues simulation of traffic flows according to the new status of traffic signals. An external module written in C facilitates the interaction between the emulator and the simulator, i.e., it sends a special signal to activate the emulator when the VISSIM simulation starts. Once the virtual controller module is written and compiled, its executable file is registered in the VISSIM using the following menu sequence:

Signal Control → Edit Signals → Type:VAP → More… button → Program File

2.4.3 Integration of Virtual Controller and VISSIM through Interfaces

Two interfaces were developed in this research to integrate VISSIM and the control emulator. The first one is the C-based VISSIM external module, whose main functions include:

- Sending simulation start signal to the virtual controller.
- getting detector data from VISSIM and write it on the Windows registry.
- getting traffic signal-head status data from the Windows registry and setting the traffic signals in VISSIM accordingly.

The important functions offered by VISSIM for the external interface module include:

- float Simulationssekunde (void);
  //Returns the current simulation second.

- void VonLSA (int kommando, int nr, BOOLEAN uebergang);
  //Sends new signal state to signal group No. <nr>, depending on the code No.

- unsigned char zaehlwert (int nr);
  //Returns the number of detected vehicle front ends since the last pass through the signal control.

The other interface is developed using the Windows registry, whose original function is the database area that stores operating system-related settings. The main advantage of the Windows registry is that it can read/write faster and more efficiently than the conventional file-based approach. Further, C/Visual Basic languages offer built-in registry manipulation functions. There are two standard function calls to access the registry with Visual Basic:

GetSetting(*appname*, *section*, *key*[, *default*])

appname	Required. String expression containing the name of the application or project whose key setting is requested.
section	Required. String expression containing the name of the section where the key setting is found.
key	Required. String expression containing the name of the key setting to return.
Default	Optional. Expression containing the value to return if no value is set in the key setting. If omitted, *default* is assumed to be a zero-length string ("").

Ex> String1 = GetSetting("TrafficSim", "Emulator", "Detector", "Error")

SaveSetting *appname*, *section, key, setting*

appname	Required. String expression containing the name of the application or project to which the setting applies.
appname	Required. String expression containing the name of the application or project to which the setting applies.
key	Required. String expression containing the name of the key setting being saved.
setting	Required. Expression containing the value that *key* is being set to.

Ex> SaveSetting "TrafficSim", "Emulator", "ControlSig", String2

In this research, the interaction between the emulator and the VISSIM simulator happens every 0.1 second. Therefore, the interface modules continuously read detector data and send traffic signal head status data every 0.1 second. The following two functions were developed as part of the external interface module that makes VISSIM interact with the Windows registry.

```
void setDetectorRegistryValue(char *value)
{
   HKEY hKey;
   /* open registry */
   RegOpenKeyEx(HKEY_CURRENT_USER,
      TEXT("Software\\VB and VBA Program Settings\\TrafficSim\\2070"),
      0, KEY_SET_VALUE, &hKey);

   /* save registry value */
   RegSetValueEx(hKey, TEXT("Detector"), 0, REG_SZ, value, strlen(value));

   /* close registry handle */
   RegCloseKey(hKey);
}
```

```
void getSignalRegistryValue(char *signalValue)
{
   HKEY hKey;
   DWORD dw_buflen = 33;
   /* open registry */
   RegOpenKeyEx(HKEY_CURRENT_USER,
      TEXT("Software\\VB and VBA Program Settings\\TrafficSim\\2070"),
      0, KEY_QUERY_VALUE, &hKey);

   /* retrieve registry value */
   RegQueryValueEx(hKey, TEXT("ControlSig"), NULL, NULL, (LPBYTE)signalValue, &dw
_buflen);

   /* close registry handle */
   RegCloseKey(hKey);
}
```

3. Modeling and Evaluation of New Minnesota Ramp Metering Algorithm with Off-line Controller Module

In this chapter, the new Minnesota ramp metering algorithm is modeled as an external control module to VISSIM and its performance was evaluated using an example freeway. The new metering algorithm generalizes the conventional zone-based control approach with new restrictions on ramp waiting time. The rest of this chapter includes the description of the algorithm, development of the external control module and simulation results with the 169 freeway.

3.1 Overview of New Stratified Zone Metering Algorithm

The goal of the new algorithm, called as Stratified Zone Metering (SZM), developed by the engineers at the Traffic Management Center, Minnesota Department of Transportation, is to determine and implement the optimal metering rates by automatically considering the time-variant bottlenecks, i.e., by adopting the overlapped zone structure and implementing the most restrictive metering rate for a given ramp from all the overlapped zones involving the ramp in question. Unlike the previous algorithm, the new one uses 'queue detectors' installed at the entrance of each ramp, as shown in Figure 3.1.1. The key component and unique feature of the SZM is the definition of overlapping zones for a given freeway section. The zone is defined as a section of freeway bounded by two mainline detector stations. The maximum length zone in the current version has six mainline detector stations and Figure 3.1.2 shows a typical definition of overlapped metering zones for a sample freeway section. Therefore, a single primary zone in the conventional zone metering will be broken down to several groups of zones, called layers, and each layer has different number of mainline detector stations. For example, the sixteen mile stretch of the northbound Highway 169 with 34 mainline stations has 178 zones, while there were only five primary zones in the previous zone metering scheme.

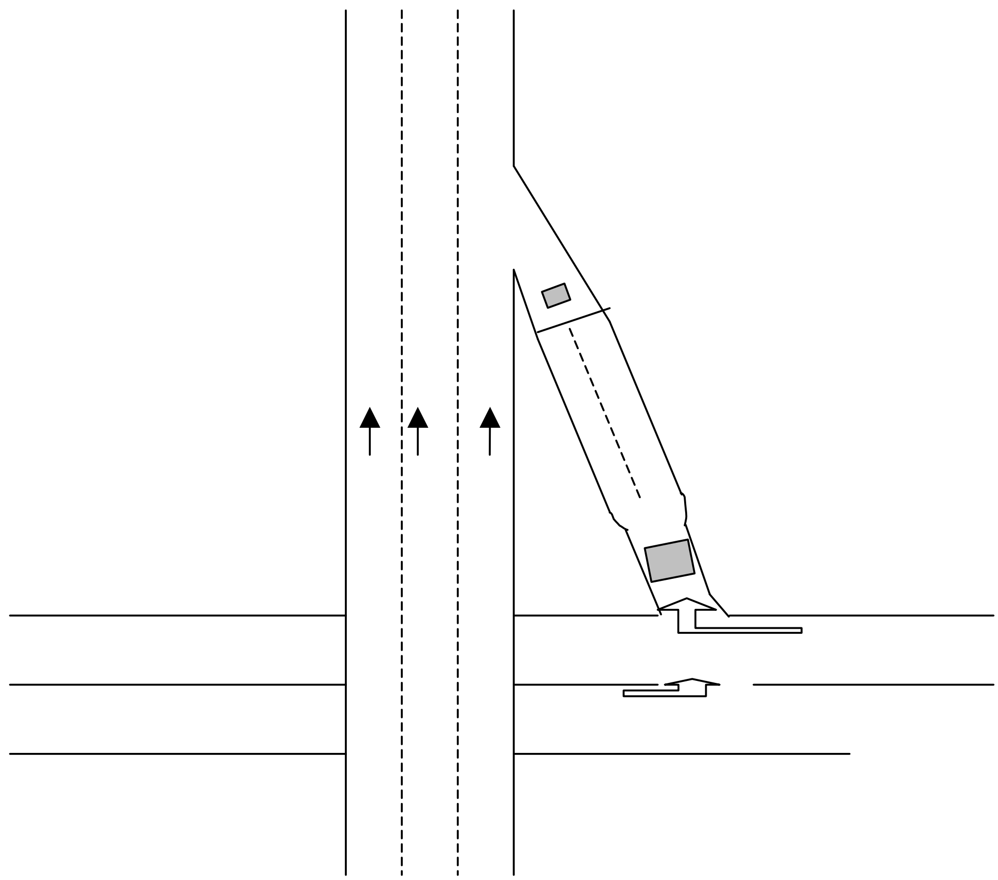


Figure 3.1.1 A typical onramp with queue and passage detector

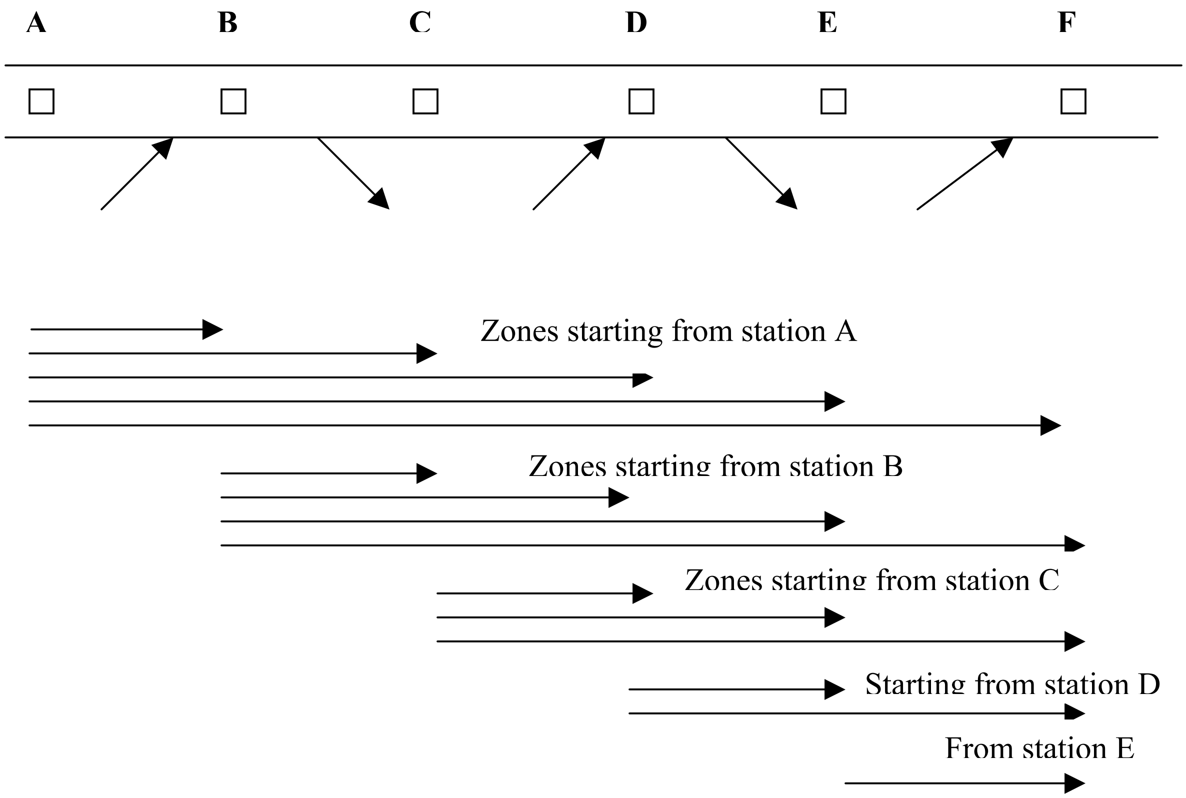


Figure 3.1.2 Zone structure in SZM

3.2 Detailed procedure of Stratified Zone Metering Algorithm

This section summarizes the algorithm of the Stratified Zone Metering (SZM) developed by the engineers at the Traffic Management Center, Minnesota Department of Transportation (2). According to the algorithm description, with SZM, the metering rates for each ramp are calculated every 30 seconds. The computed rates are then converted into red times that remain constant over a 30 second time interval. The basic equation used to obtain metering rates is the same traffic flow conservation equation used in the previous zone metering, i.e.,

$$M + A + U <= B + X + S \text{.............................Eq 1}$$

where, M= Total volume entering the mainline from all entrance ramps in a given zone,

A = Arrival volume at the upstream boundary of a zone,

U = Total volume entering a zone from un-metered entrance ramps,

B = Capacity of downstream mainline boundary of a zone,

X = Total exit volume from a zone,

S = Available storage, or spare, capacity in the beginning of each time interval.

As 30-second data is very volatile, detector volumes are estimated for each 30-second interval using smoothed volumes detected during last time intervals. A simple linear smoothing function as shown in Eq 2 is used for this purpose:

$$F_t = F_{t-1} + K * (G_t – F_{t-1}) \text{.............................Eq 2}$$

where F_t is the smoothed value for the current time interval, F_{t-1} is its last estimated value, G_t is the current detection value on which Ft is dependent and K is a smoothing constant. This smoothing function is iterative and is supplied with initial value, F_0, for the first iteration. The value of the constant, K, typically lies between 0 and 1. When K is set to 1, smoothing is disabled, while changes become more gradual as K approaches zero. In equation 1 the values A, U and X are computed every 30 seconds using equation 2.

$$A_t = A_{t-1} + K * (A_t – A_{t-1}) \text{.............................Eq 3}$$

$$U_t = U_{t-1} + K * (U_t – F_{t-1}) \text{.............................Eq 4}$$

$$X_t = X_{t-1} + K * (X_t – F_{t-1}) \text{.............................Eq 5}$$

The value of B, the expected downstream mainline capacity for each zone, is variable with a typical value between 1800vphpl to 2200vphpl. Spare Capacity, S, gives an insight into whether a zone is empty or full in the beginning of each time interval. If the average density in the zone is less than the critical density, i.e., 32 vehicles per mile, then the difference between the current density and the critical density multiplied by the number of lane-miles in the zone is used as the spare capacity. Bad detectors are not included in the average density calculation.

Once all values are obtained the maximum release rate, M is obtained. Each meter rate is set based on its demand. Demand, D_t, is the flow rate of vehicles entering a ramp and is computed by smoothing 30-second queue detector counts, Q_t, The smoothing function for D_t is:

$$D_t = D_{t-1} + K * (Q_t - D_{t-1}) \quad \text{......................Eq 6}$$

However, when a ramp queue becomes long and extends beyond a queue detector, ramp demand cannot be computed using the above equation as the number of vehicles waiting upstream of the queue detector is not known. Such situation results in high occupancy at the queue detector. If queue detector occupancy goes above a threshold value of 25%, ramp demand is calculated using the following equation:

$$D_t = D_{t-1} + 150 \quad \text{......................Eq 7}$$

As metering rate depends on demand, this method ensures a higher metering rate for that particular ramp. When there is no queue detector or when a queue detector malfunctions, passage detector counts are used to estimate demands. The equation to estimate demand in such a case is:

$$D_t = D_{t-1} + K * (1.1*P_t - D_{t-1}) \quad \text{......................Eq 8}$$

In the above equation passage detector counts, P_t, are increased by 10% to account for the fact that passage detectors are located downstream of a ramp meter.

To ensure that waiting times are limited to preset values, minimum release rate for each meter is computed. The final value of a metering rate for any meter cannot be set below the minimum release rate for a given ramp. Demand calculation partly takes care of this problem by not letting vehicles to backup till the queue detector. The other case that needs to be looked at is the case when vehicles are stored between queue detector and ramp meter. In such a situation the number of vehicles that are queued on the onramp is obtained from the queue storage length and the queue density of an onramp.

Queue density of each onramp is estimated with the accumulated release rate, R^a_t, which is obtained by smoothing the current release rate, R_t.

$$R^a_t = R^a_{t-1} + K * (R_t - R^a_{t-1}) \quad \text{......................Eq 9}$$

Since queue densities increase if metering rates are restrictive, an empirical relationship given in equation 10 is used to obtain queue density, N, from the accumulated release rate.

$$N = (2280 - R^a) / 8 \quad \text{......................Eq 10}$$

From queue density and storage length, L, the number of vehicles waiting on an onramp, T, can be obtained as following:

$$T = N * L /5280 \text{……………………………Eq 11}$$

It is assumed that queue will be 100 feet from the queue detector when the queue threshold occupancy level, 25%, is attained. Therefore the storage length for an onramp is calculated as,

$$L = 2 * (d' – 100) \text{…………………………..Eq 12}$$

Where d’ is the distance from the meter stop line and the queue detector as shown in Figure 3.2.1.

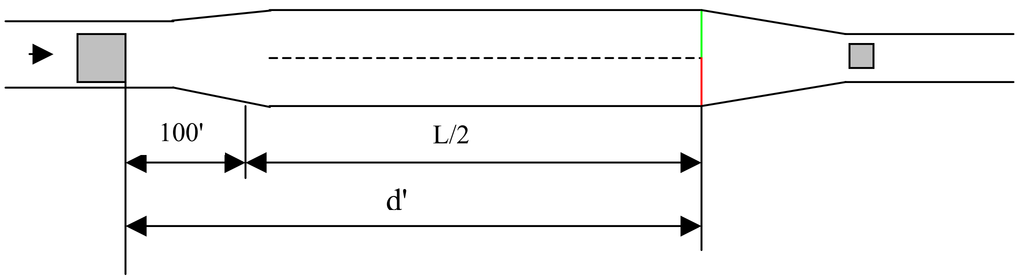


Figure 3.2.1 Storage length for a ramp

Cycle time for each ramp is obtained from the preset waiting time (four minutes or two minutes depending on the ramp type) and the number of vehicles waiting on the ramp.

$$C^{max} = 240 \text{ (seconds in four minutes) / T for normal on ramps………..Eq 13}$$

$$C^{max} = 120 \text{ (seconds in four minutes) / T for freeway-to-freeway ramps…..Eq 14}$$

Minimum release rate, R^{min}, is obtained from the maximum cycle time using the following equation:

$$R^{min} = 3600 \text{ (seconds in one hour) / } C^{max} \text{ ………..Eq 15}$$

For those ramps without queue detectors or when the queue detector occupancy exceeds threshold occupancy value, the minimum release rate is set to the demand of the corresponding ramp. Absolute minimum release rate is 240vph (two vehicles in 30 seconds) and if computed minimum release rate falls below 240, it is set to 240vph. One problem with this approach is that minimum release rate for ramps with large storage lengths will be very high. This is evident from the above equations and is illustrated in the following table by showing the contrast between two ramps with same queue densities.

Table 3.2.1 Problem with minimum release rate computation

Density (N)	Storage length (L)	Max. vehicles in Q	Max. Cycle time (s)	R^{min}
235	240	11	21	240
235	760	33	3	990

This problem has potentially serious consequences, as freeway-to-freeway ramps that typically have large storage lengths and a low preset maximum waiting time tend to get higher metering rates. To address this problem, the metering rates for these ramps are never set higher than the demand computed from the passage detector counts as long as the queue occupancy is below the preset threshold occupancy.

After obtaining maximum release rates for each zone and minimum release rates for individual ramp meters, the next step is to get the actual metering rates. This stage known as *rule processing* is an iterative process. The number of rules for a freeway is equal to the number of stratified zones. Final values of computed metering rates should satisfy all the rules. To begin rule processing, the rule demand (D^{rule}) for each zone is calculated by adding the estimated demands of all the meters in that zone.

$$D^{rule} = D^1 + D^2 + D^3 + \ldots\ldots\ldots\ldots + D^n$$

Proposed metering rate (R^p) for each meter is calculated next using the following equation:

$$R^p = M * D / D^{rule}$$

3.3 Development of an Off-line Controller Module for Stratified Zone Metering

In this study, an external control module that can interact with VISSIM is developed to emulate the metering process of the new algorithm described in the previous section. While VISSIM has a built-in fixed-time controller, in this study, an off-line external control module is also developed for the fixed metering, since alternating green signals with two signal heads at a ramp, the current standard practice of Mn/DOT, cannot be handled easily with the built-in functions of VISSIM. Ramp meters in VISSIM are treated like signal heads and red time intervals can be changed from an external controller. In fixed metering these red timings are predetermined and do not vary with time and green times are always fixed at 1.3 seconds with an amber time of 0.7 seconds. Figure 3.3.1 shows the structure of the off-line virtual metering controller module developed for the new algorithm.

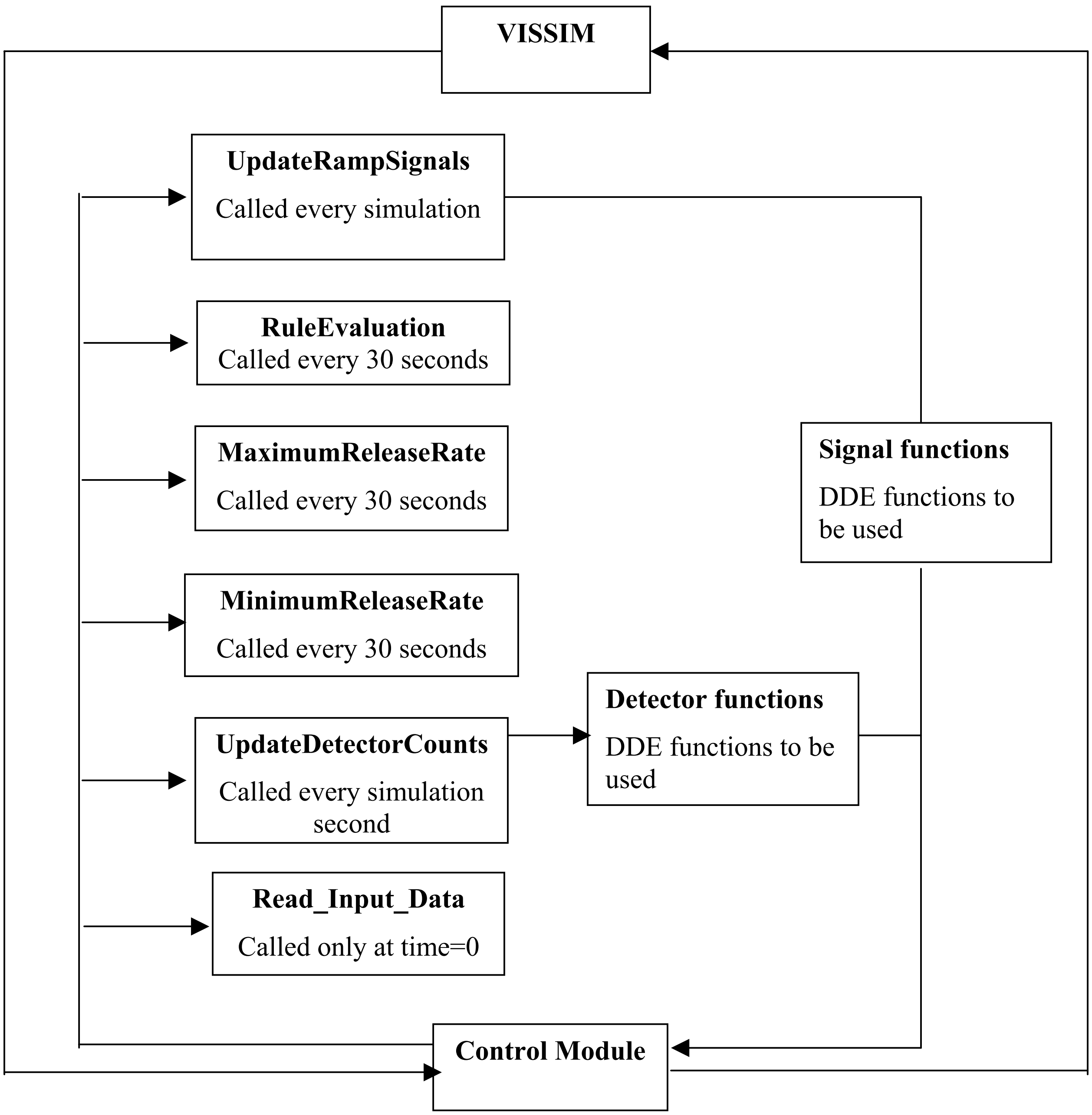


Figure 3.3.1 Structure of the Virtual Controller Module for New Metering Algorithm

3.4 Simulation of the new metering algorithm with VISSIM

3.4.1 Overview of the sample freeway section

The new metering algorithm coded into the external controller module was simulated with VISSIM using the northbound TH-169 as the test freeway section. The geometry network data was obtained from the aerial photographs of Eden Prairie, Hopkins and Osseo counties. Those photos were used as the background maps and the detailed road network was developed using the network editing functions of the VISSIM as explained in Chapter 2. The test freeway section is 18 miles long with the upstream boundary at I-494 interchange and the downstream boundary at 63rd avenue north. It has 34 mainline stations, 17 metered ramps and 10 un-metered entrances. A total of 156 loop detectors including mainline, passage, queue, off-ramp and HOV sensors, are located in the test section. Of the 17 metered ramps, queue detectors are installed at 13 ramps and all the metered ramps have two queue-lanes. There are four HOV ramps un-metered. All the meters have two poles with alternating greens and only one car is allowed to enter the mainline per green. Entrances are metered both during the AM and PM peak hour periods. The unique feature of the test section is the 10 weaving sections that are located contiguously. Figure 3.4.1 shows the geometry modeled in VISSIM using the aerial photos as the background map.

3.4.2 Data Collection

Figure 3.4.2 shows the types of input data required by VISSIM. Traffic data consisting of detector volume and occupancies was extracted for two days: September 20th and September 25th of 2001. The volume data at each entrance ramp was checked for consistency and given as input demand data for VISSIM. Turning proportions were estimated using volume data from upstream, downstream and off-ramp detectors as shown in Figure 3.4.3. When vehicles reach a decision point, section A in the figure, they can either exit the freeway or continue to move along the freeway. In VISSIM such a location known as the routing decision point needs the data regarding the percentage of vehicles that exit and the percentage of vehicles that continue along the freeway. These turning proportions should be specified in 5-minute intervals. In this study, the turning proportions are calculated using the following equations:

$$TPX = X / (A + M) * 100$$

$$TPF = B / (A + M) * 100$$

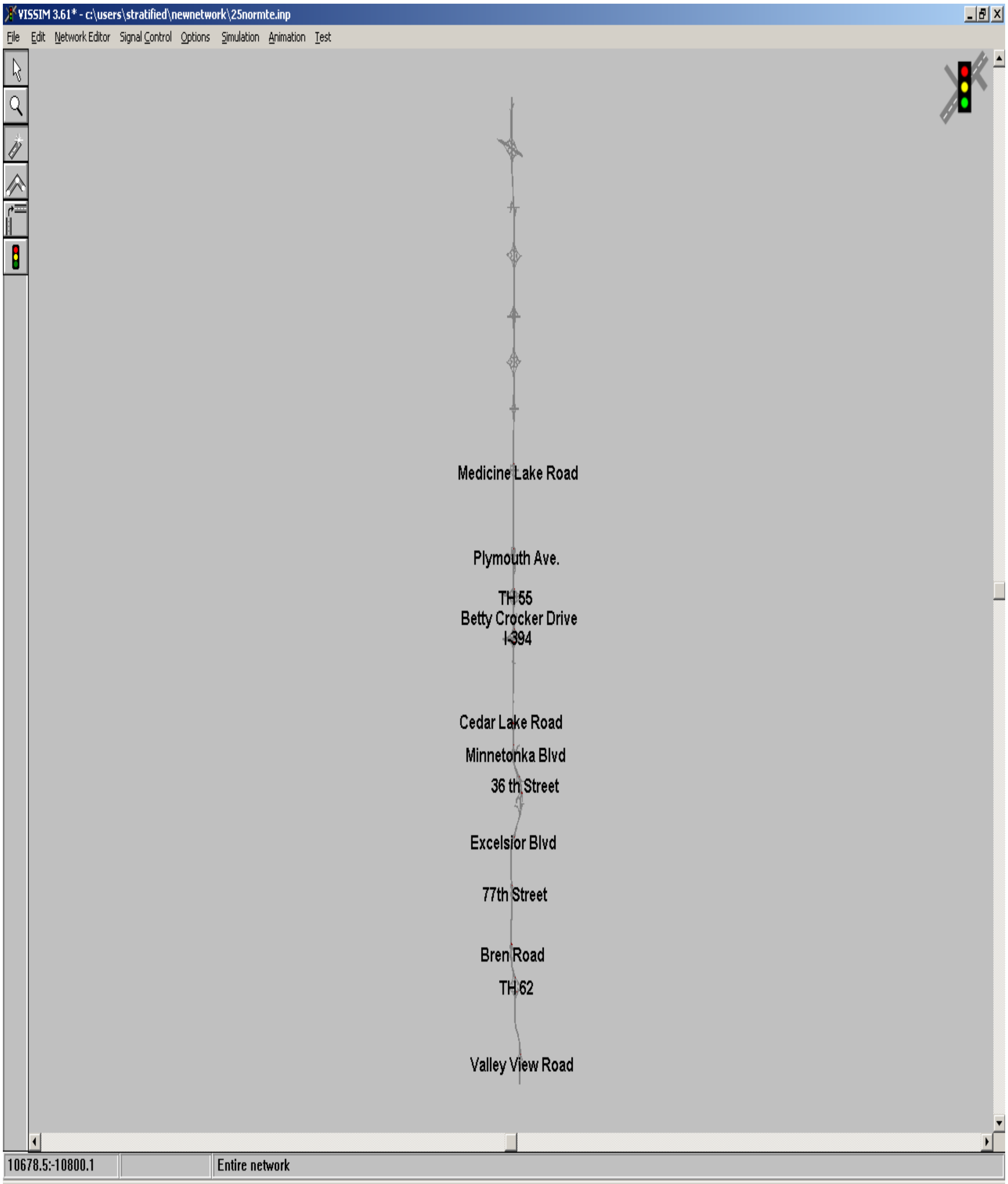


Figure 3.4.1 The geometry of the test freeway section, 169NB, modeled in VISSIM

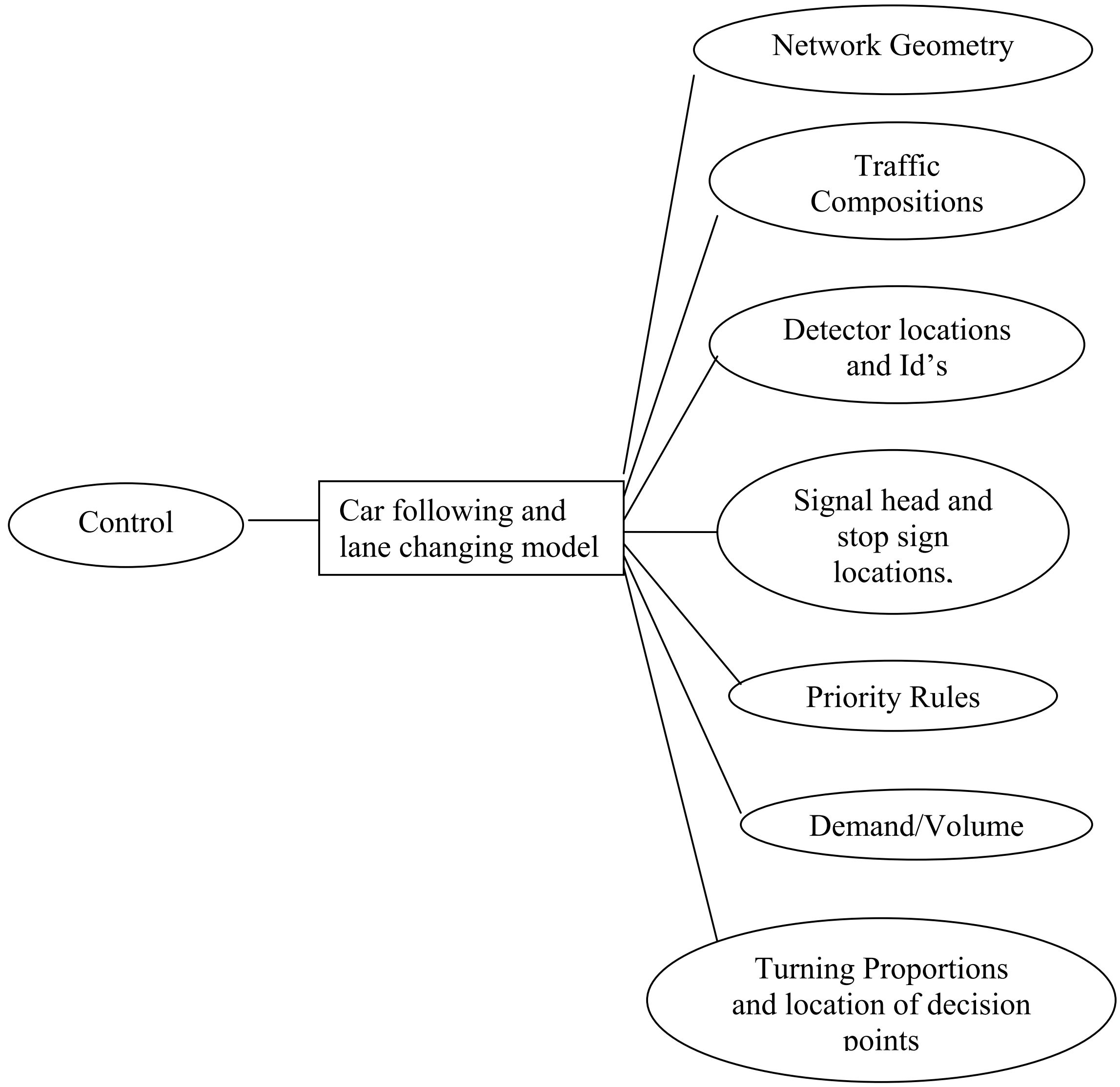


Figure 3.4.2 Required input data for VISSIM simulation

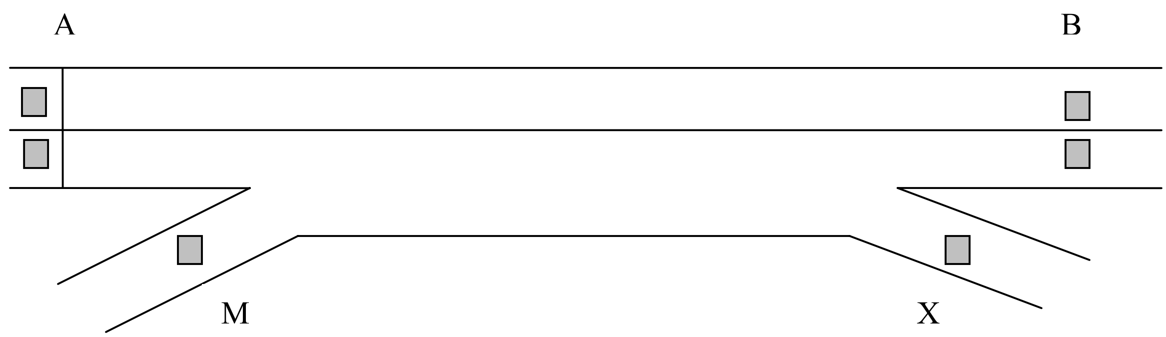


Figure 3.4.3 Example section for turning proportion calculation

Further, a C program was written to automate the data entry process for demand allocation and turning movement percentages with the loop detector data. It is important to note that the location of the routing decision point can affect the simulation results. If it is located too close to an exit ramp, vehicles may try to exit from the left lanes blocking the mainline traffic. Further, it cannot be placed too far from an exit ramp, since it may result in too early lane-changing of the exit vehicles.   The determination of the routing decision point location needs to be a part of the calibration process for a given freeway system.

Metering Data

In this study, the fixed-metering control was used as the base case to compare the performance of the new metering algorithm.   Table 3.4.1 shows the fixed metering rates and corresponding red time intervals used for the entrance ramps in the test section in this study.   For the simulation of the new stratified zone metering algorithm, the current zone structure being operated in the test freeway section was used. Figure 3.4.2 shows the current overlapping zone structure, which has up to six layers.

Table 3.4.1 Fixed metering rates for the test freeway section

Ramp	Red Times	Cycle Time	Metering rate/ pole	Metering Rate
Valley View	4	6	600	1200
EB 62	3.5	5.5	655	1309
WB 62	3.7	5.7	632	1263
Bren Road	4.3	6.3	571	1143
7th/Lincoln	13.5	15.5	232	465
Excelsior	4.3	6.3	571	1143
TH 7	5	7	514	1029
36th	9.6	11.6	310	621
Minnetonka	9.6	11.6	310	621
Cedar Lake Road	14.9	16.9	213	426
EB 394	3	5	720	1440
WB 394	3	5	720	1440
Betty Crocker Dr	9.2	11.2	321	643
EB 55	9.6	11.6	310	621
WB 55	8.8	10.8	333	667
Plymouth Road	7.2	9.2	391	783
Medicine Lake Road	6.8	8.8	409	818
36th Ave	-			
EB Rockford Road	-			
WB Rockford Road	-			
49th Ave	-			
EB Bass Lake Road	-			
WB Bass Lake Road	-			
63rd Ave	-			

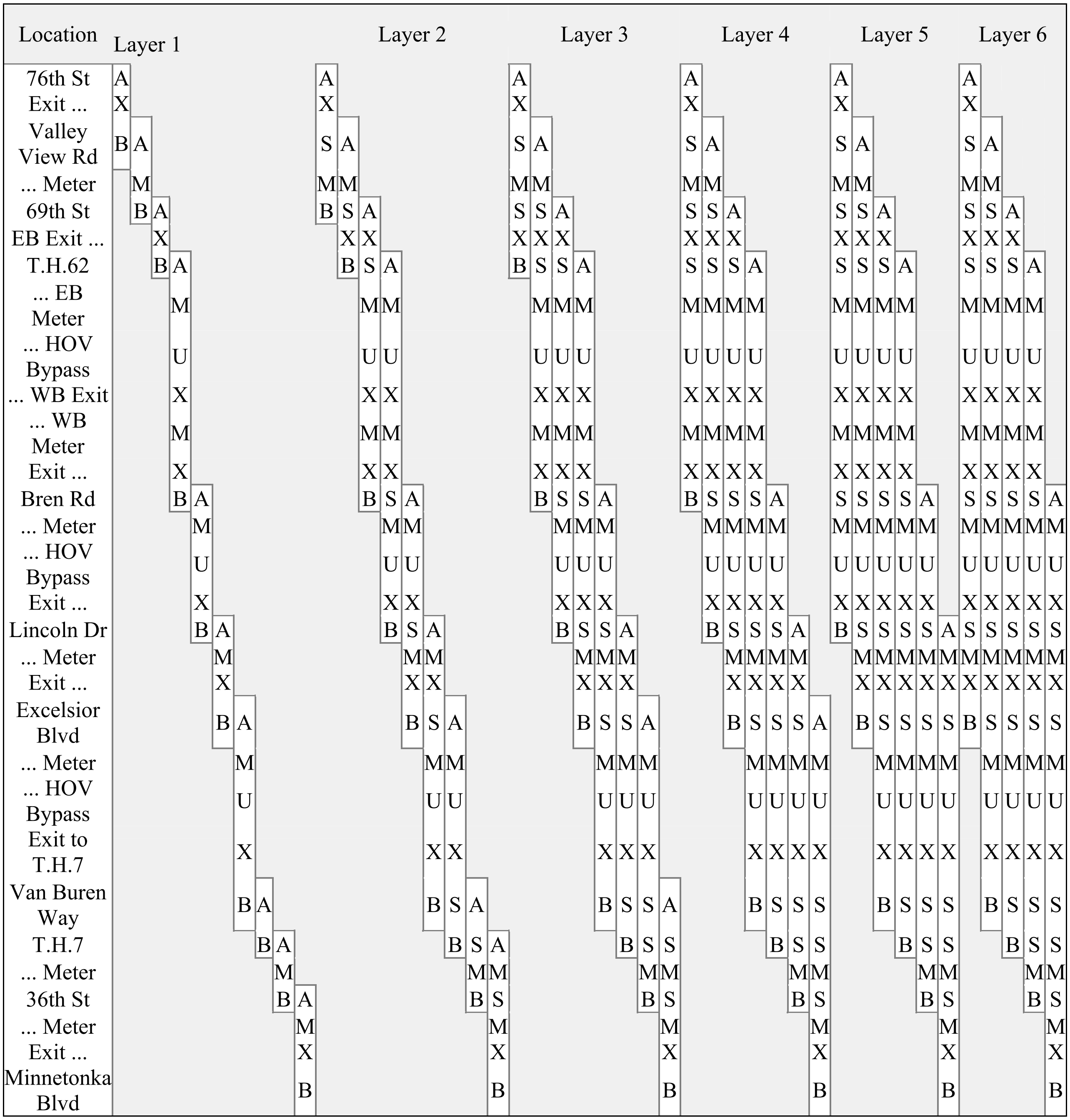


Figure 3.4.4 Configuration of overlapping zones for new metering algorithm

3.4. 3 Calibration of VISSIM for Test Freeway Section

Calibration of a model is an iterative process in which the model's parameters are adjusted to replicate actual traffic conditions as closely as possible. In this research, the traffic volume data collected on September 20th and 25th, 2001, were used for calibration. Since the fixed metering control was implemented on those two days, the calibration was conducted by simulating the sample freeway with the same fixed-metering rates as in the real case and by adjusting the parameters in the car-following model to minimize the difference between simulated and measured traffic data at the detector locations. Traffic composition for this network consisted of trucks and passenger cars with the percentage of trucks being 3% of the total entering traffic for the entire simulation period. Default values of vehicle parameters like length and width were used for simulation as these values represent the average values observed in United States. Turning proportions were calculated as described in the last section.

Collection of the simulated data was conducted at pre-specified data collection points for mainline segments. One of the difficulties in calibrating the test section lies in the location of contiguous weaving sections. VISSIM removes vehicles from the network if they do not merge onto their designated routes within a pre-specified time. This time known as the *waiting time before diffusion* defines the maximum amount of time a vehicle can wait at an emergency stop position waiting for a gap to change lanes in order to stay on its route. Typically this value is set to 10 seconds for freeway segments and can be treated as a simulation parameter. If this value is high, vehicles tend to wait on the freeway stopping the mainline traffic, and if a low value is used the number of lost vehicles due to diffusion may rise and traffic on the network may be well below observed values. To minimize the number of lost vehicles and to ensure smooth weaving behavior, local speeds in the vicinity of all weaving sections were restricted to the speed limits posted on the field. In modeling weaving sections, special care has to be taken so that vehicles do not exit from the left most lane within a weaving section. Further, the vehicles which do not exit through the off-ramp in a weaving section should not move onto the right-most lane. Therefore for every weaving section a parameter, called the lane change parameter, is set such a way that no lane changing is permitted in a weaving section. This value is specified in the downstream connector that connects a weaving section to the mainline segment of a freeway. The modeling of a weaving section is illustrated in Figure 3.4.5 and 3.4.6.

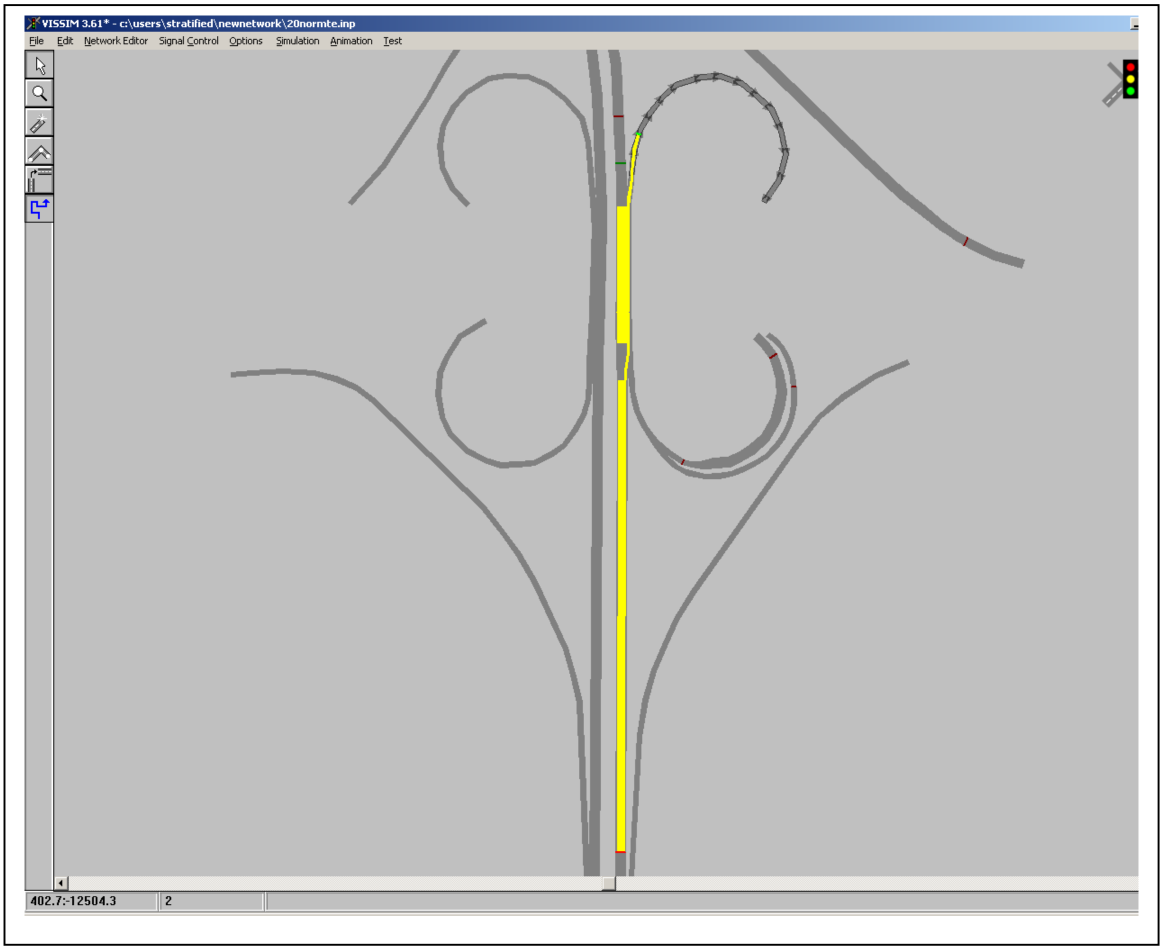


Figure 3.4.5 Example weaving section and specification of route-decision in VISSIM

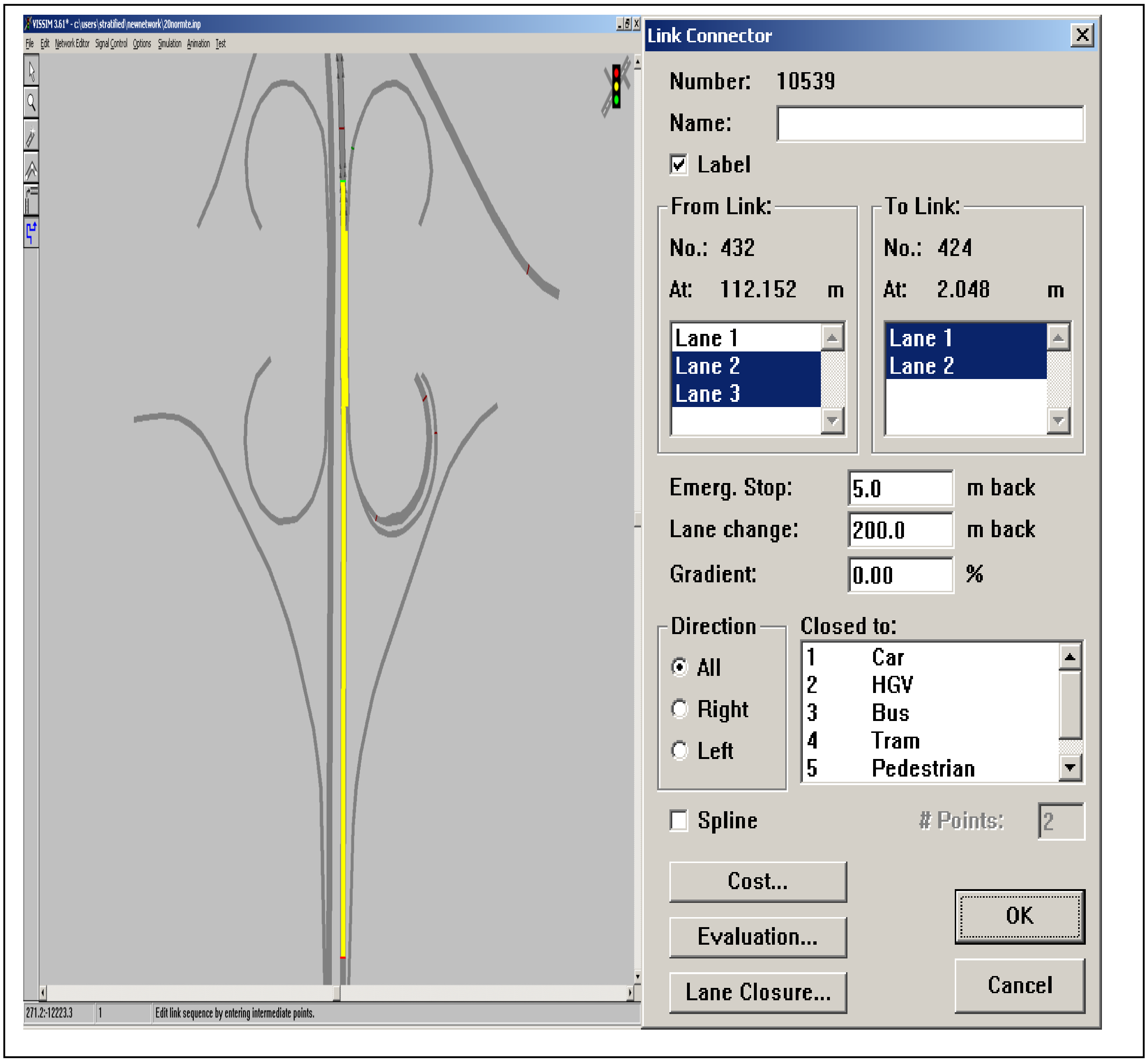


Figure 3.4.6 Specification example for weaving section

Other global parameters that affect the simulation results include number of simulation seconds per time step, desired speed distributions, acceleration and deceleration rates for each vehicle class. The number of simulation seconds per time step (resolution) indicates how often the location of vehicles on a network is updated by the simulation module. The higher the speed of a section the higher the resolution needs to be. For the sample freeway section, 10 simulation seconds per time step were used.

In this study, the VISSIM model was calibrated by systematically adjusting the parameter values for the car-following models until the differences between the simulated volume and the real measured data at the same detector locations are within a reasonable range. Tables 3.4.2 and 3.4.3 include the resulting parameter values after calibration. Figures 3.4.7 and 3.4.8 show the comparison results between the simulated and the measured volumes at two different mainline locations, i.e., middle and downstream locations. The pink line in the graphs represents simulated values and the blue line represents actual measured volumes. As indicated in these graphs, the simulation results closely follow the traffic pattern or congestion trend of the real measured data.

3.4.5 Simulation of the new metering algorithm

Once the network was calibrated for fixed ramp metering, the next step was to implement the new metering algorithm and compare the performance of the new algorithm with that of the fixed metering case. In this study, the test freeway section was simulated with the two metering schemes for different demand conditions and random seeds. The measures of effectiveness' (MOE's) used for comparison include ramp travel times for all the metered ramps and speed variations at selected locations on the mainline. Further the total throughput, i.e., total volume entered the mainline from the upstream boundary and from all the entrance ramps in a test section in every 5 minutes is also used for comparison. To estimate travel time at an entrance ramp, 'Travel time sections' were specified on all the metered ramps as shown in the Figure 3.4.9. Travel time section needs to be specified to measure the time taken by vehicles to cross the ramp meter after they enter an onramp. The travel time and speed data were collected in 5-minute intervals.

Figures 3.4.10-3.4.13 show the comparison results between the fixed and the new metering performance in terms of ramp travel time and mainline speed variations at selected locations. As indicated in these figures, the new metering scheme resulted in slightly more restrictive control than the fixed metering by inducing longer, but not significantly higher, ramp travel times at most metered entrance ramps. This resulted in slight improvements of the mainline speeds, i.e., higher and less fluctuation through time than the fixed-metering cases, as also shown in the figures.

Table 3.4.2 Vehicle parameters

Parameter	Passenger Car	Trucks	Units
Length	4.21	8.5	m
Width	1.75	2.5	m
Maximum Acceleration	4.1	2.8	m/s^2
Maximum Deceleration	7.5	6.0	m/s^2
Desired Deceleration	2.8	1.3	m/s^2
Desired Speed	85-120	80-100	Km/h

Table 3.4.3 Car-following model parameters

Parameter	Value	Units
Waiting time before diffusion	10	s
Minimum headway	0.2	m
Maximum deceleration for necessary lane change	3	m/s^2
Number of observed vehicles	2	-
Minimum look ahead distance	0	m
Maximum look ahead distance	250	m

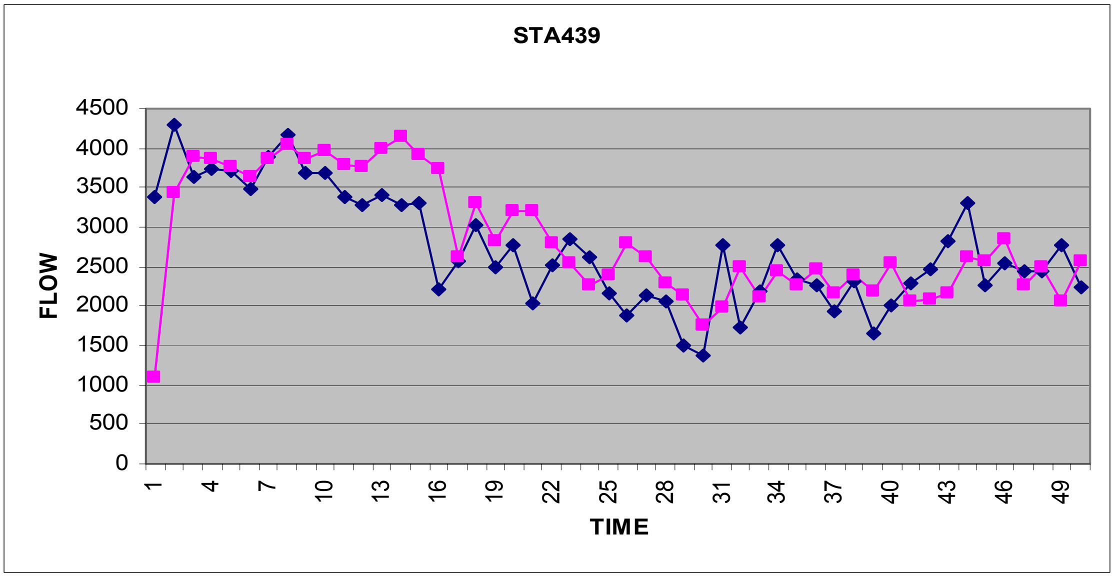


Figure 3.4.7 Comparison results at middle point (station 439)

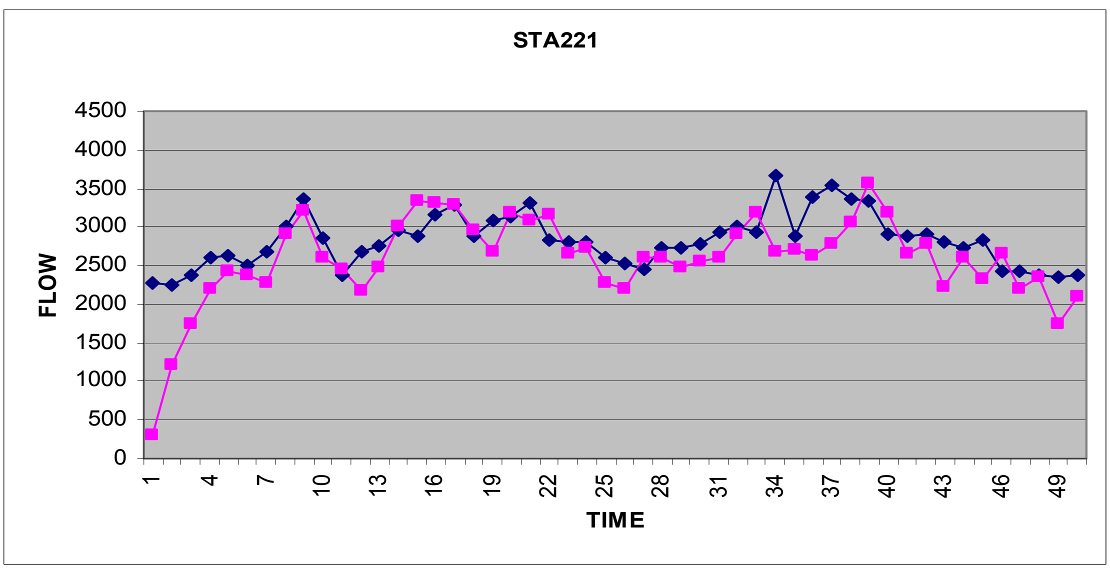


Figure 3.4.8 Comparison results at downstream locations (station 221)

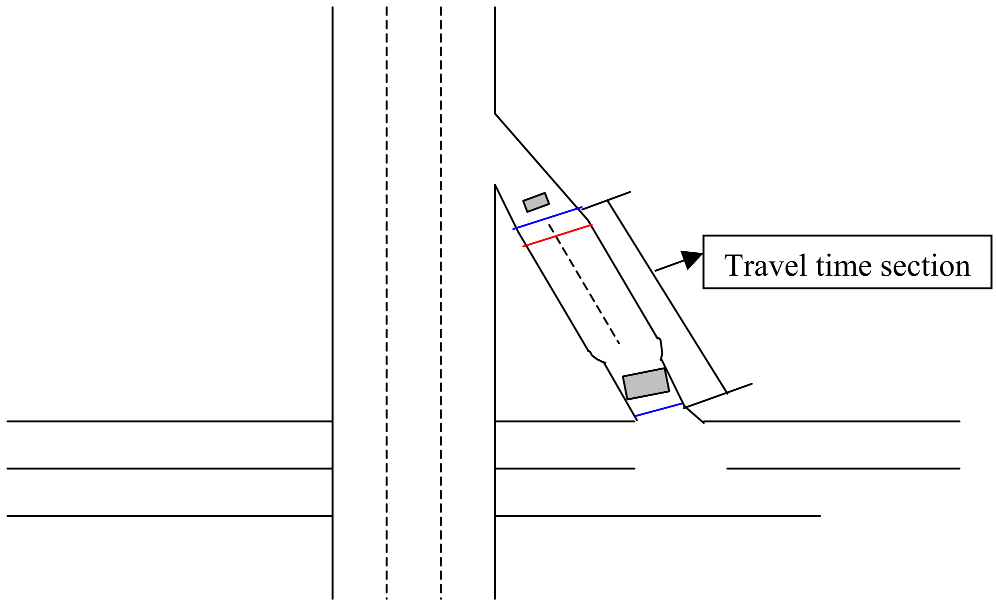


Figure 3.4.9 Travel time section specification at on-ramp

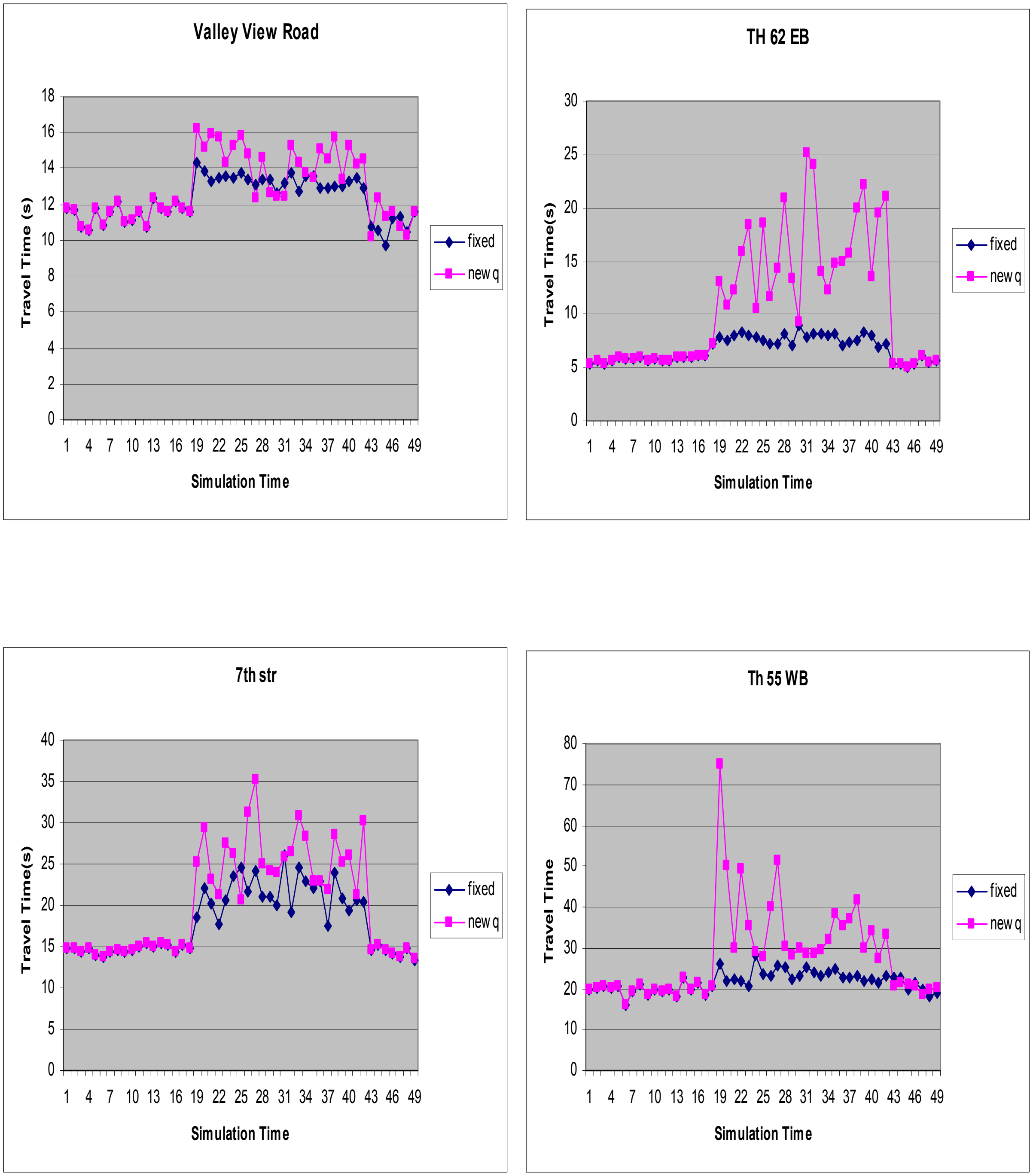


Figure 3.4.10 Comparison results of Ramp Travel Time between Fixed and New Metering (with 9/20 demand data and random seed 62)

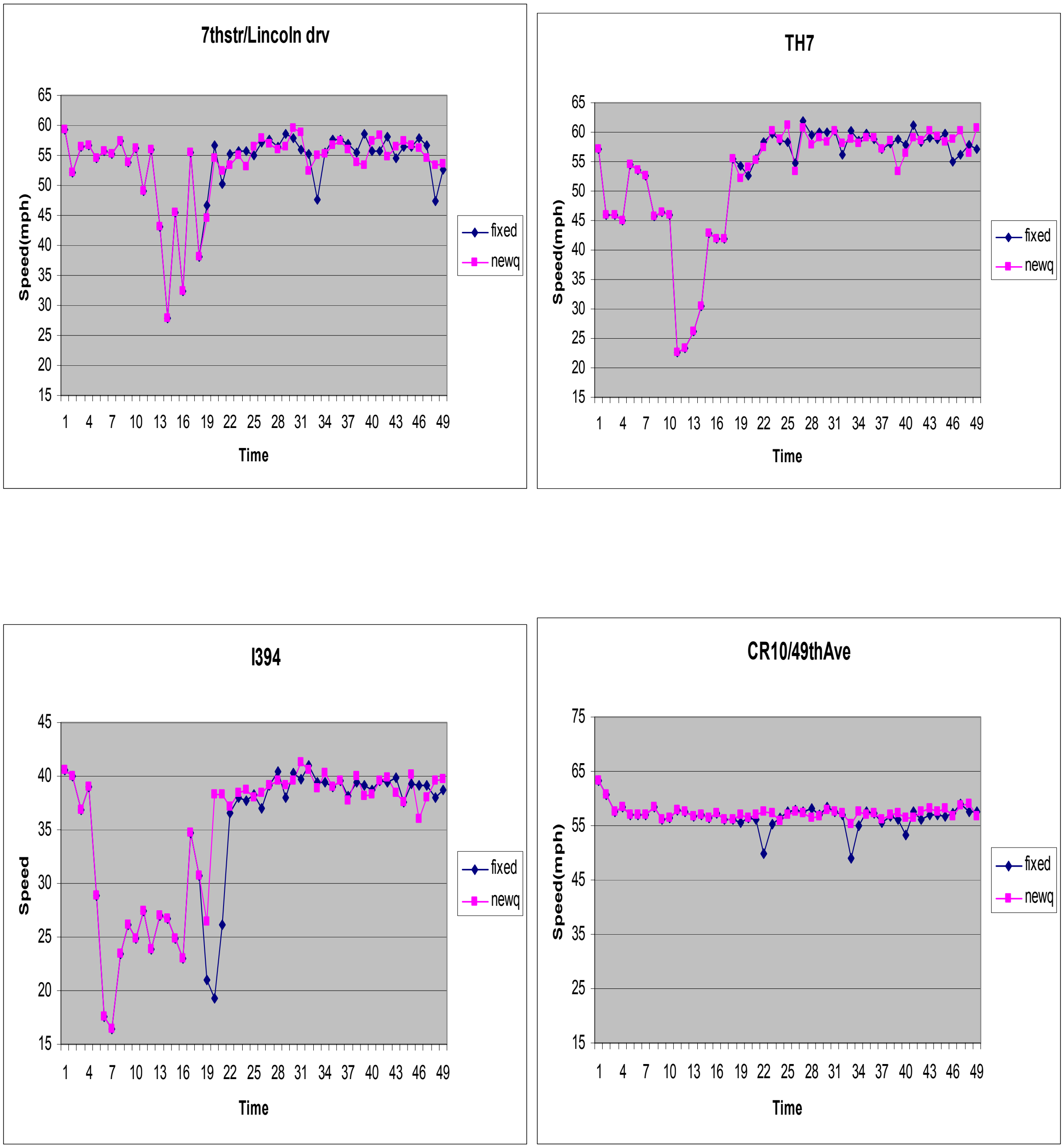


Figure 3.4.11 Comparison results of Mainline Speed between Fixed and New Metering (with 9/20 demand data and random seed 62)

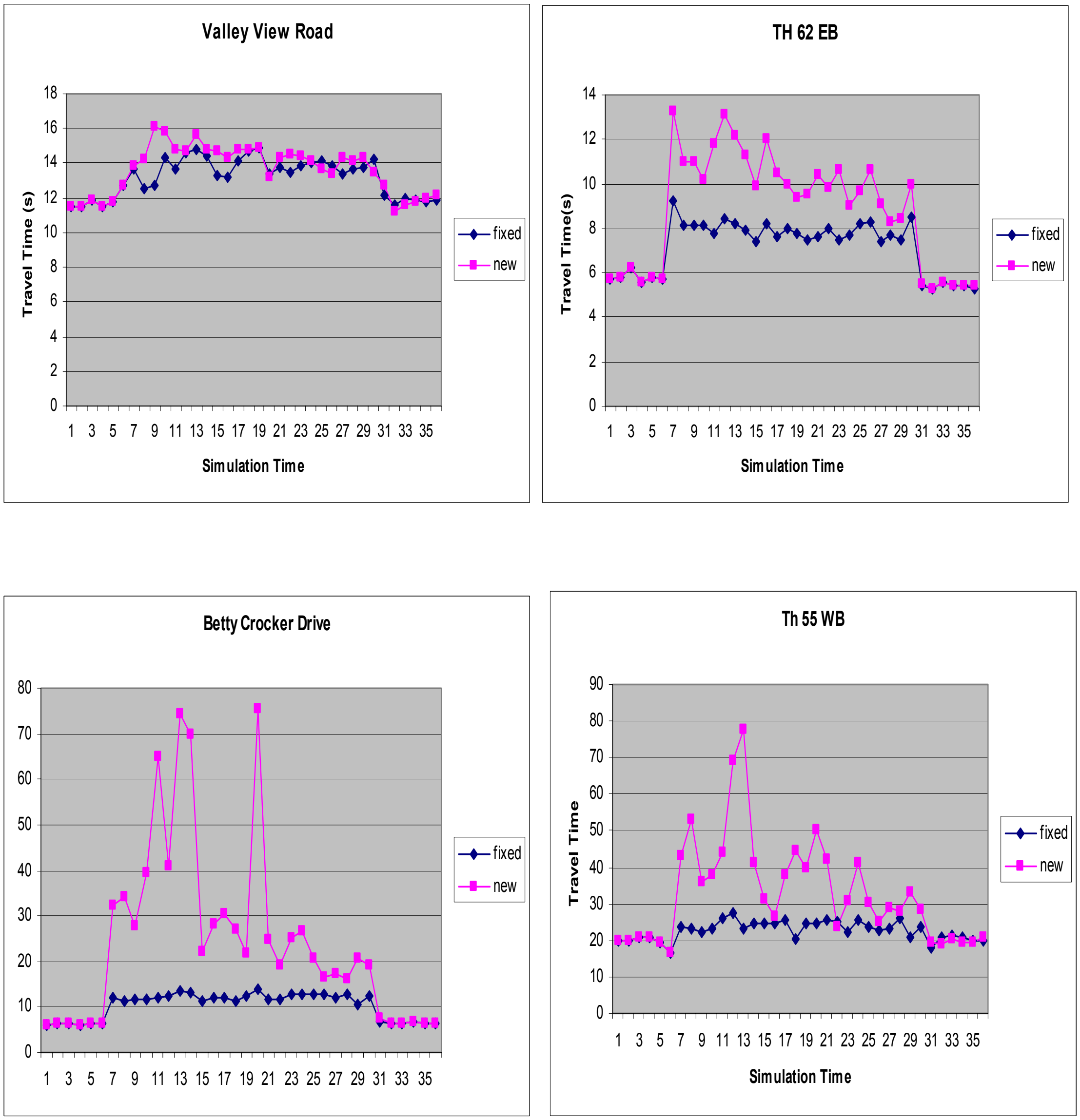


Figure 3.4.12 Comparison results of Ramp Travel Time between Fixed and New Metering (with 9/25 demand data and random seed 32)

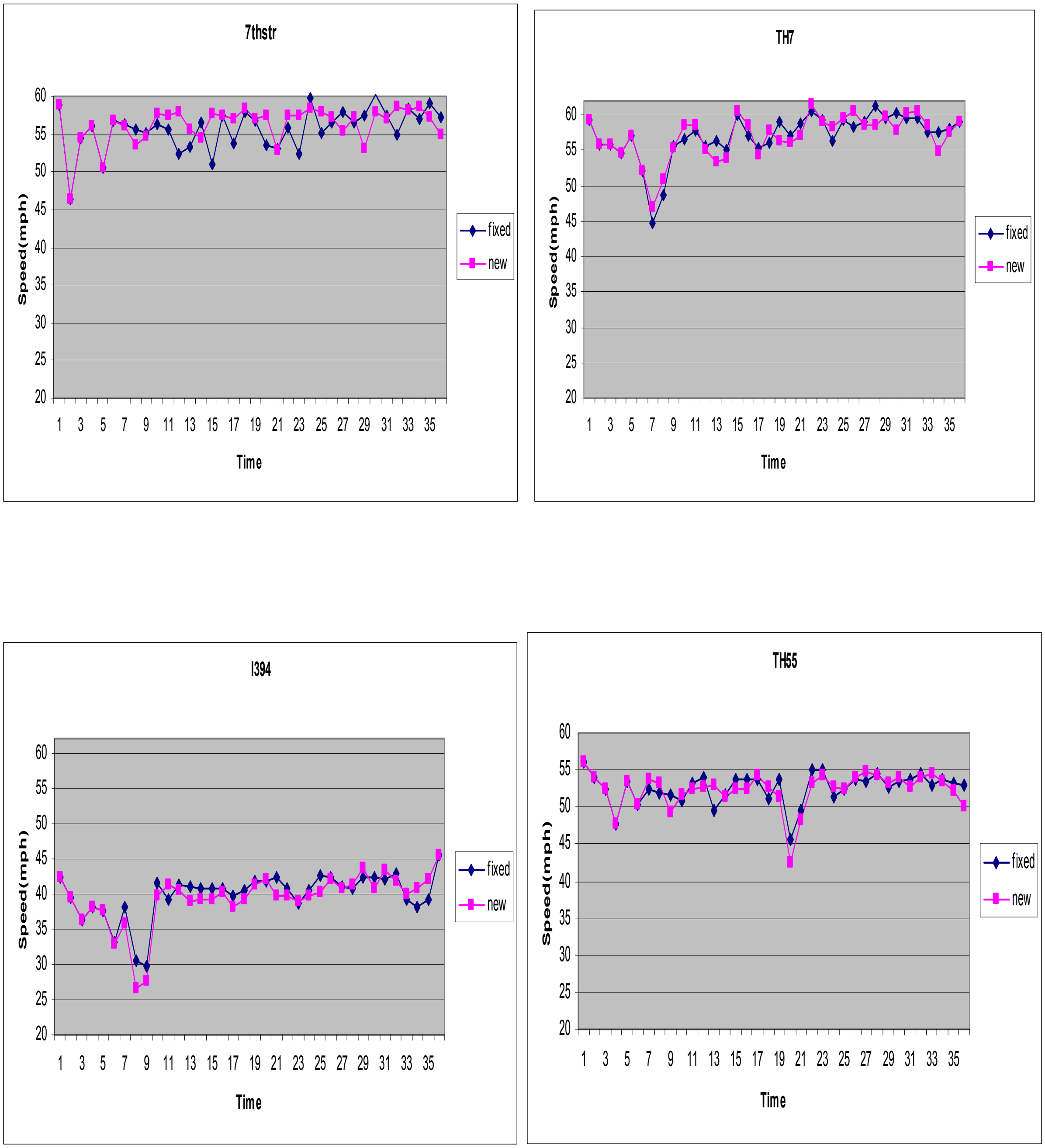


Figure 3.4.13 Comparison results of Mainline Speed between Fixed and New Metering (with 9/25 demand data and random seed 32)

It needs to be noted that the new metering scheme resulted in ramp travel times much shorter than the pre-set threshold values, i.e., 4 minutes for normal ramps and 2 minutes for freeway-to-freeway ramps. It indicates the relatively conservative nature of the current algorithm in terms of the ramp queue management and also opens the possibilities for future improvement of the algorithm.

3.5 Development of an Alternative Method for Determining Minimum Metering Rates

To address the difficulties in ramp queue management, an alternative method to determine the minimum metering rate for an entrance ramp is developed in this study. The new method is based on the conventional cumulative input/output curve through time, where a horizontal line between two curves indicates the waiting time of a vehicle after it arrived at a system until it leaves. Figure 3.5.1 shows the cumulative arrival/departure curves for an entrance ramp through time. Assuming that the current state of the system is at (1) and the cumulative departure volume at the end of next 30 second interval will be at (2), the length of the horizontal line between (2) and (3) denotes the projected waiting time for the vehicle arrived at the entrance ramp at time (3). This projected waiting time would be the maximum possible waiting time of vehicles arrived by the time (3). Therefore, by comparing this value with the pre-set threshold maximum waiting time, a new cumulative departure volume can be determined to make the projected maximum waiting time of the vehicles waiting at the ramp equal to the pre-set threshold value as illustrated in Figure 3.5.2. Then the minimum metering rate for this particular ramp can be determined as the difference between the projected cumulative departure volume and the cumulative departure volume by the current time step. The step-by-step algorithm for this procedure can be written as follows:

1) Assume that (1) is current time and store last 10 30-second cumulative volumes.
2) Add 'Absolute Minimum Release Rate' to the current value.
3) At that height go left until you meet the incoming graph line.
4) Calculate the distance from (2) to (3).

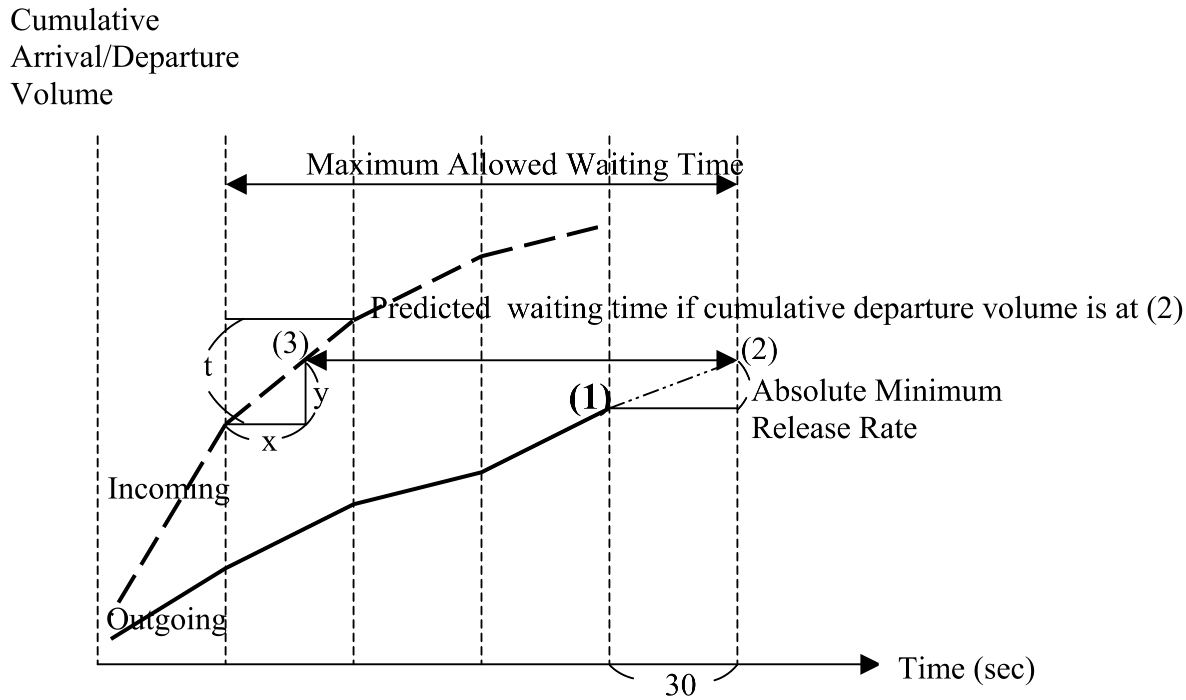


Figure 3.5.1 Predicted ramp waiting time on arrival/departure curve

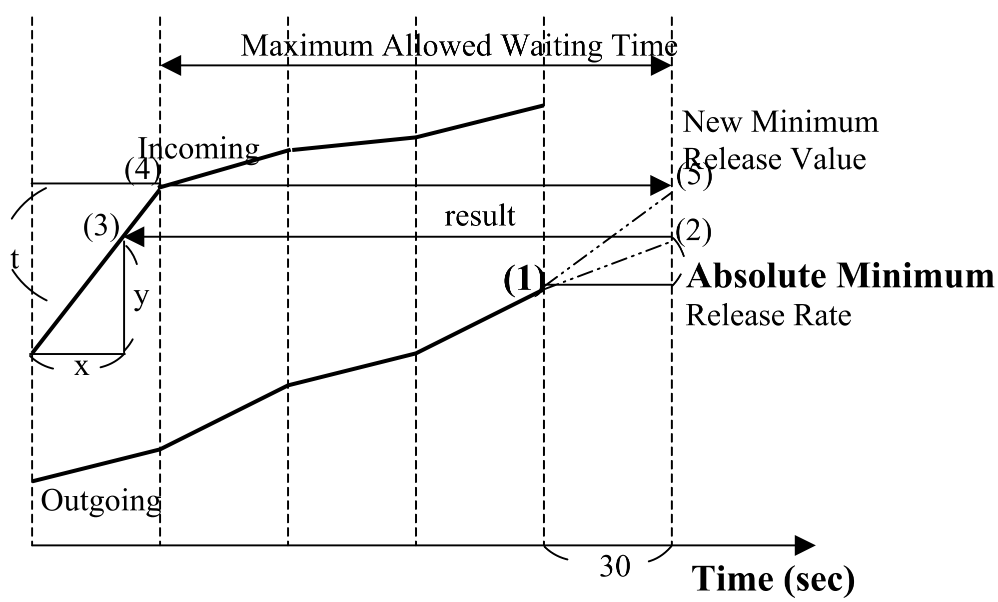


Figure 3.5.2 Determination of new minimum metering rate satisfying pre-set maximum allowable Time

5) If the result is less than 'Maximum Allowed Waiting Time',
   then 'Absolute Minimum Release Rate' is minimum release rate.
   Otherwise, go up along the incoming graph.
   The increased value is minimum release rate

In this research, only the source code for the above algorithm is developed. The actual implementation with the simulation module can be conducted in the future study.

Source code for New Minimum Metering Rate calculation procedure

```
// Step (2), add 'Absolute Minimum Release Rate' to current outgoing value.
next_value = meter->outgoing[9] + ABSOLUTE_MIN_RELEASE_RATE;

// Step (3), find the point which has the same value on the incoming graph.
for (j=9; j>=1; j--)
{
        if (meter->incoming[j] >= next_value && meter->incoming[j-1] < next_value)
                break;
}

// Step (4), calculate the distance from (2) to (3)
t = (float)(meter->incoming[j] - meter->incoming[j-1]);
y = (float)(next_value - meter->incoming[j-1]);
x = (float)(y * 30 / t);
result = 30 - x + (30 * (10 - j));

// Step (5), calculate the minimum release rate.
if (result < meter->max_allowed_wait_time)
{
        meter->min_release_rate = ABSOLUTE_MIN_RELEASE_RATE;
}
else
{
        j = (int) (meter->max_allowed_wait_time/ 30);
        meter->min_release_rate = meter->incoming[10 - j] - meter->outgoing[10 - 1];
}
```

4. Development of an Adaptive Coordinated Control Strategy for a Ramp-Intersection Area

4.1 Literature Review of Coordinated Control Strategies for Traffic Networks

Development of practical and robust on-line strategies that can automatically determine coordinated control solutions between ramp meters and adjacent intersection is an essential element in improving traffic management in freeway networks. While there has been substantial amount of research conducted in the area of optimal corridor control, the current state-of-the-art in traffic control has not reached the point where optimal coordinated solutions are generated and implemented in real time. To be sure, most research effort to date adopts the classical optimal control approach, which formulates the corridor control as a non-linear optimization problem with origin/destination demand patterns, turning proportions and simplified traffic models (3-5). These approaches require accurate prediction of time-dependent origin/destination flow patterns and diverted flow with almost perfect detection of traffic flows, which may not be possible in real world applications. An approach by Wu and Chang (6) tries to estimate turning proportions in real time, but adopts a two-segment equilibrium flow-density relationship on both freeway and arterial traffic flows with boundary traffic demand assumed to be given by an external module. Recently Gettman, et. al. (7) proposed an adaptive control approach with prediction/optimization of queue size at the intersections near a freeway ramp assuming the departure rates at the ramp meter can be predicted in real time for next control interval. As indicated above, most corridor control methods appeared in the literature employ some form of prediction models for vehicle arrivals, departures and turning movements to determine an 'optimal' control solution. Therefore, the quality and effectiveness of control solutions substantially depends on the accuracy of prediction. However, the possibility of developing of reliable on-line predictors is still in question considering various random factors affecting traffic behavior and the decision-making process of drivers. The research effort to develop practical coordinated control methods that do not depend on on-line prediction or analytical optimization has been relatively few. Pooran, et.al. (8) evaluated different levels of tactical coordinated control strategies using microscopic simulation and reported 5-10% reduction of total delays, while the detailed procedures of their methods were not published. Han and Reiss (9) tried to find optimal metering rates considering upstream intersection signal states, but used simplified assumptions for the arrival demand patterns at an entrance ramp.

4.2 Development of a Coordinated Adaptive Control Strategy and Virtual Controller

Figure 4.2.1 shows a typical freeway entrance area in Minnesota and the simplified structure of the proposed control strategy is illustrated in Figure 4.2.2, where the control area is divided into freeway, intersection and ramp sub-areas. For each control interval, the proposed strategy first calculates the congestion index of each sub-area with the data from field detectors. The congestion index quantifies the level of congestion on a 0 to 1.0 scale for a given roadway segment with the commonly available data, such as volume and presence. The congestion indices of both freeway and intersection area are then used by the adaptive metering module, which adapts the metering control rule to reflect the current traffic conditions and determines the metering rate for the next control interval. The adaptive signal module makes phase change decisions depending on the congestion level of freeway ramp area and each approach.

4.2.1 Congestion Index

The congestion index used in this study quantifies an area or link-wide congestion level by combining the point measurements from each detector in a given area or link as follows:

$$C_{i,k} = \Sigma\, \beta_j (P_{j,k} + V_{j,k})/(1 + Vj_{,k}).$$

$V_{j,k}$ = number of vehicles passed detector j in link i during k,

$P_{j,k}$ = 1.0 if detector j is occupied by a vehicle at the end of k,

0.0 else.

β_j = weight for detector j in link i, $\Sigma\, \beta_j = 1.0$

In the above formula, $C_{i,k}$ represents the congestion level of link i during k on a 0 to 1.0 scale using only volume and presence detection commonly available from loop detectors (10,11). Further, by adjusting the value of β_j for certain detection points, such as bottleneck area or left-turn stop line, the congestion index can reflect different types of control policies or link conditions. For example, the current stop-line based, actuated control method being implemented by the City of Minneapolis can be modeled by using the congestion index, i.e., by setting all the weight values as zero except those detectors at a stop line.

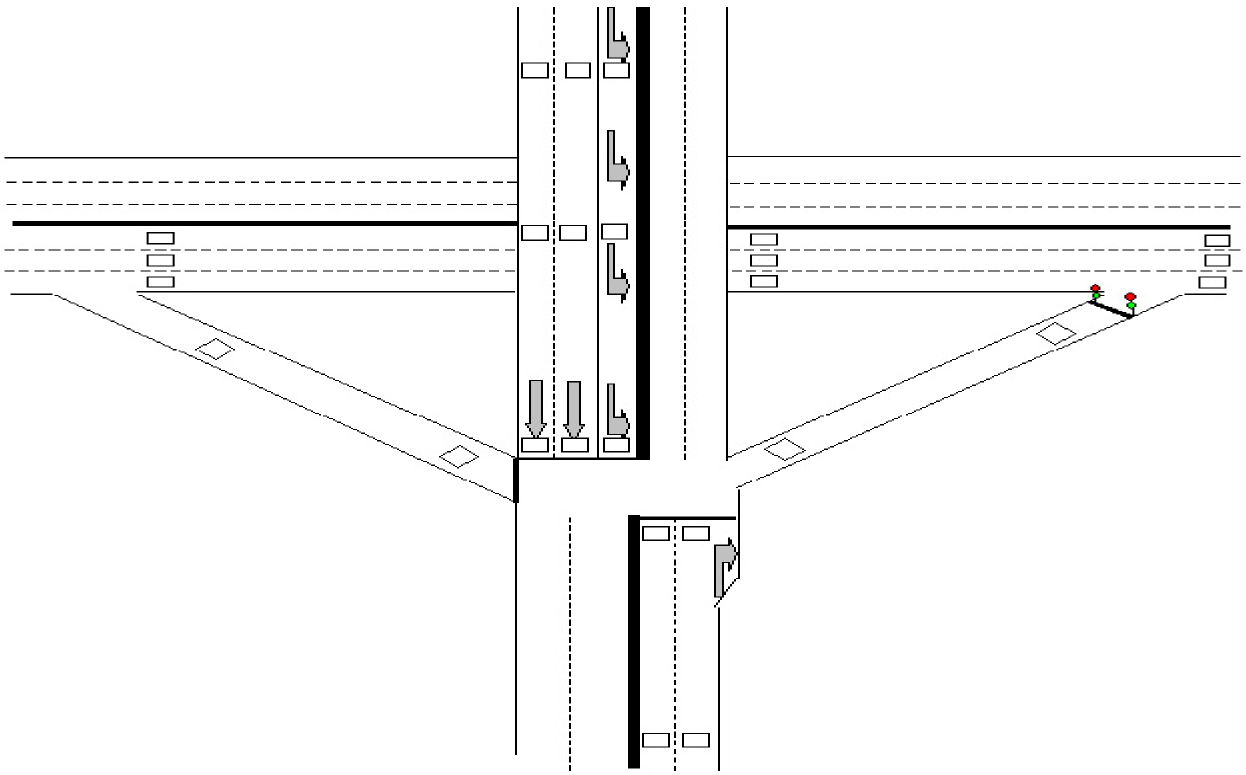


Figure 4.2.1 Typical freeway entrance ramp area

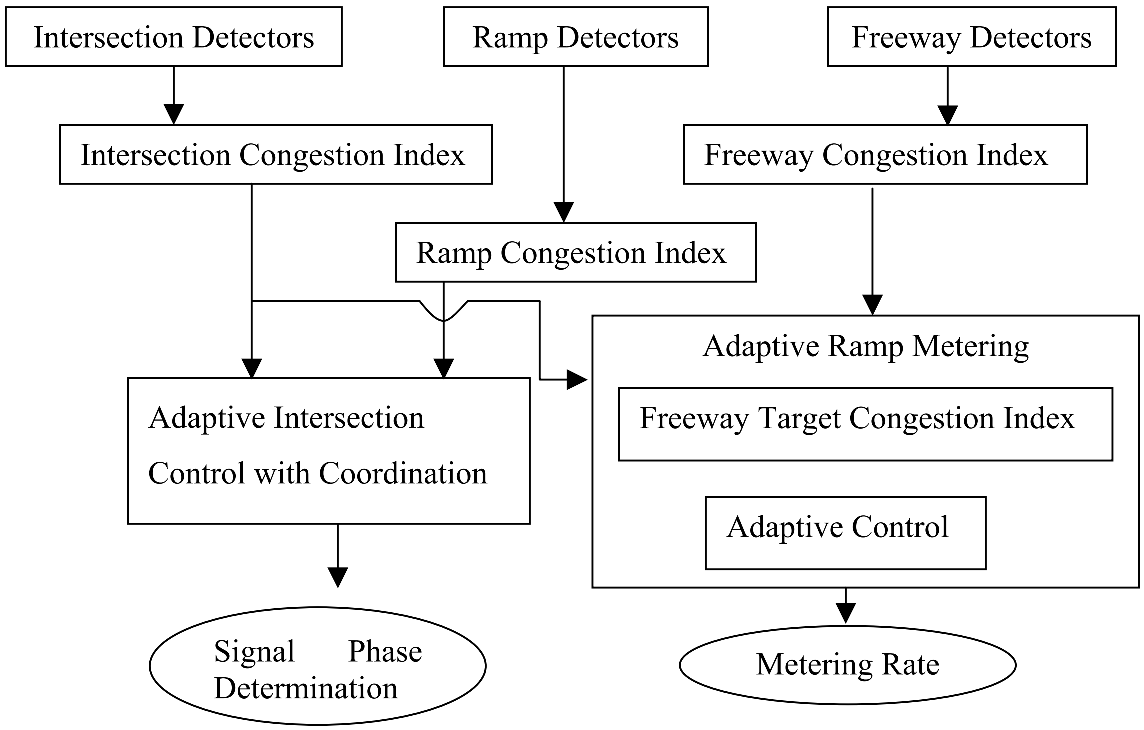


Figure 4.2.2 Simplified structure of coordinated adaptive strategy

4.2.2 Adaptive Ramp Metering

In the adaptive metering module proposed in this study, the metering rate is continuously adjusted every control interval to reflect the congestion levels of both freeway and intersection areas, i.e.,

$$R^{t+1} = R^t * \alpha^t$$

where, R^t is the metering rate for control interval t and α^t is the adjustment factor that is determined through the adaptive strategy, which is illustrated in Figure 4.2.3. As indicated in the figure, the adaptive metering strategy proposed in this study tries to make the congestion level of a given freeway area as close to the target congestion level as possible during the next control interval by either increasing or decreasing the current metering rate, i.e., by adjusting α^t values as follows:

$$\text{if } \; C_{T,F}^{\ t} - C_F^{\ t} > 0, \quad \alpha^t = 1 + (1 - C_F^{\ t} / C_{T,F}^{\ t})(R_{max}/R^t - 1)$$

$$= 0, \quad \alpha^t = 1.0$$

$$< 0, \quad \alpha^t = 1.0 - (C_{T,F}^{\ t} - C_F^{\ t})(1 - R_{min}/R^t)/(C_F^{\ t} - 1)$$

where, $R_{min} <= R^{t+1} <= R_{max}$

$C_{T,F}^{t+1}$ = target congestion index for freeway.

In the above formula, $C_{T,F}^{t+1}$ is determined by examining the congestion indices of both freeway and intersection areas, i.e.,

If $C_A^{\ t} < = C_F$

then $C_{T,F}^{\ t+1} = C_{T,F}$

else $C_{T,F}^{\ t+1} = C_{T,F} * [1.0 + \gamma(C_A^{\ t} - C_F^{\ t})]$

where, $C_A^{\ t}$ = Congestion Index for Intersection area during time interval t,

C_F = Desired level of Freeway Congestion Index to achieve maximum throughput,

$C_F^{\ t}$ = Congestion index for Freeway area during time interval t,

γ = parameter to reflect sensitivity of control policy with respect to intersection congestion.

The above strategy tries to maintain the freeway congestion level near the desired optimum value as long as the intersection area is not congested. When the congestion level of the intersection area is higher than that of the freeway, then the target congestion index for the freeway is increased for the next control interval. This results in higher metering rate than the current one, so that more vehicles can be entered the freeway segment. While the goal of the proposed strategy is to

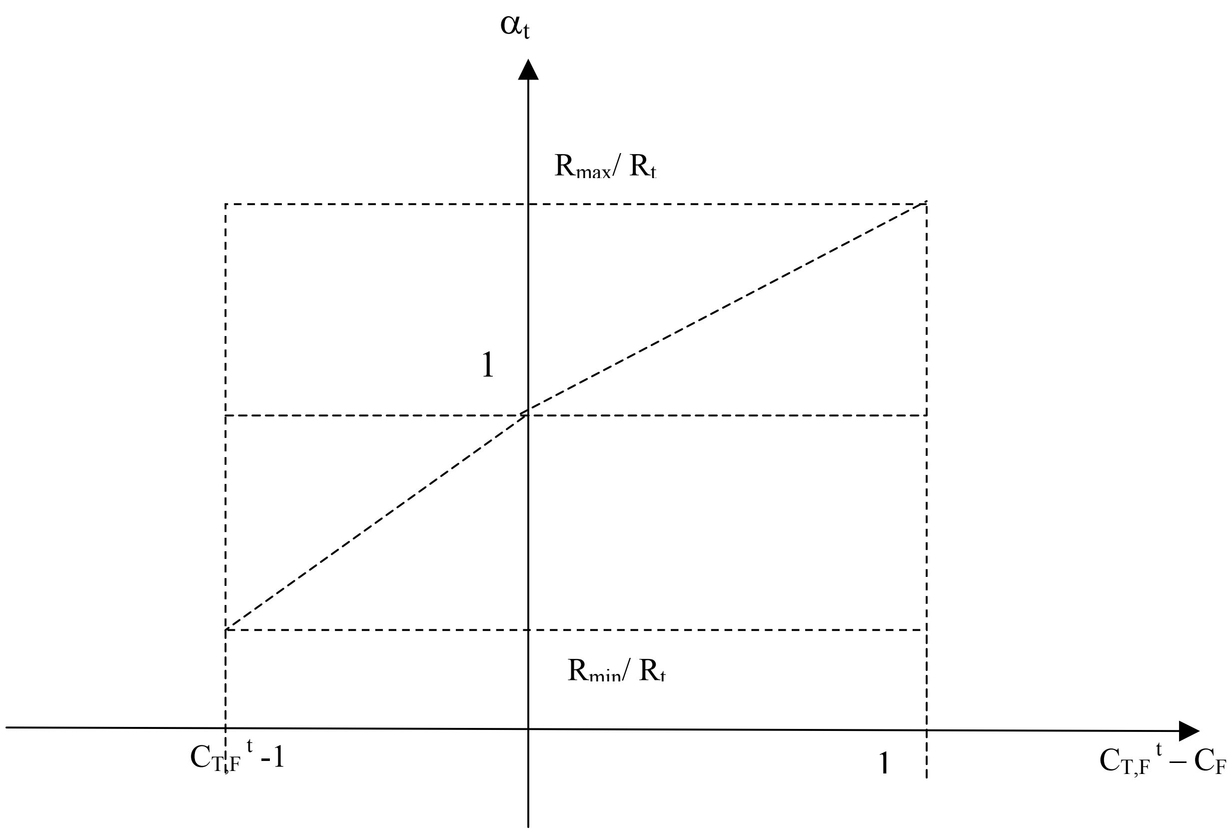


Figure 4.2.3 Adaptive control strategy for ramp metering

achieve the balanced operation between freeway and adjacent intersection areas, by adjusting γ value, the proposed method can reflect certain preferential control policy toward either freeway or arterials.

4.2.3 Adaptive Intersection Control

The adaptive intersection control approach used in this study is based on the common structure of the actuated control method, i.e., it follows pre-determined phase sequence and each phase has minimum/maximum duration intervals. However, it uses the link congestion index defined above and quantifies the congestion level of the current phase as well as that of the next phase by simultaneously cumulating the congestion indices of all the active links in the current phase and those to be activated in the next phase. After the minimum duration of the current phase expires, the algorithm compares the cumulative congestion index of the current phase with that of the next phase. If the next phase congestion index is greater or equal to the current phase congestion level, then the control switches to the next phase; otherwise, the current phase is extended until the next extension check time. In particular, the traffic conditions at the freeway ramp area are directly reflected in determining the activation or extension of the left-turn phase. As indicated above, the proposed intersection control method uses link-wide traffic condition rather than point measurements in making phase change decisions. Although the current version of the new control uses a fixed phase sequence and constant extension intervals, the use of the congestion index allows the possibility of introducing variable minimum/maximum phase duration and extension intervals depending on the level of congestion at each approach. Figure 4.2.4 illustrates the process of the adaptive intersection control with coordination.

4.2.4 Development of a Virtual Controller for VISSIM

A virtual controller is developed for the proposed coordinated control method to be implemented with VISSIM following the methodology developed in Chapter 2. Figure 4.2.5 shows the structure of the virtual controller for the coordinated control. It can be noted that the structure of the virtual controller for coordinated control was designed such a way that multiple ramps can be coordinated with multiple intersections and different types of control algorithms can be easily implemented under the current framework.

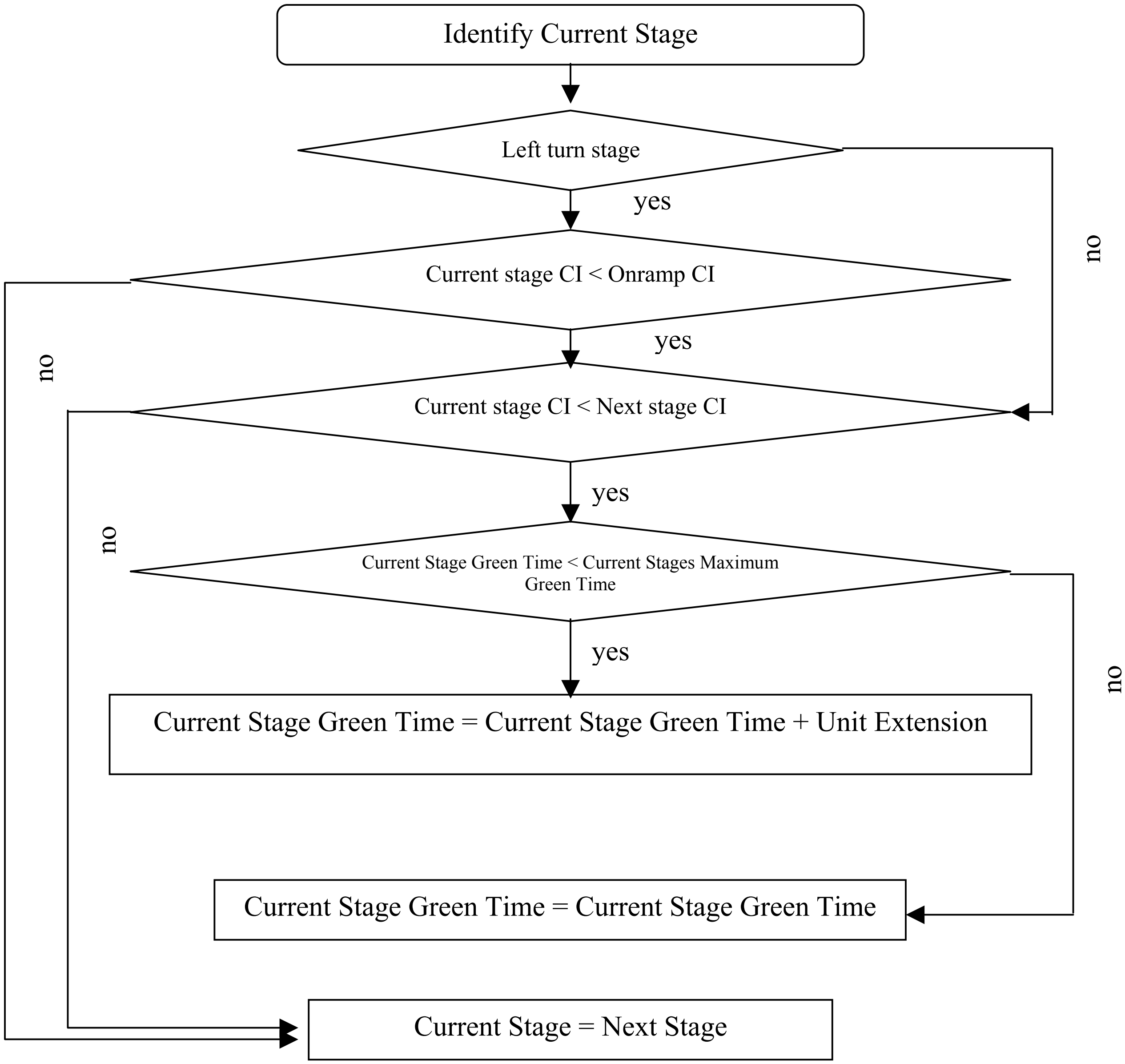


Figure 4.2.4 Process for adaptive intersection control with coordination

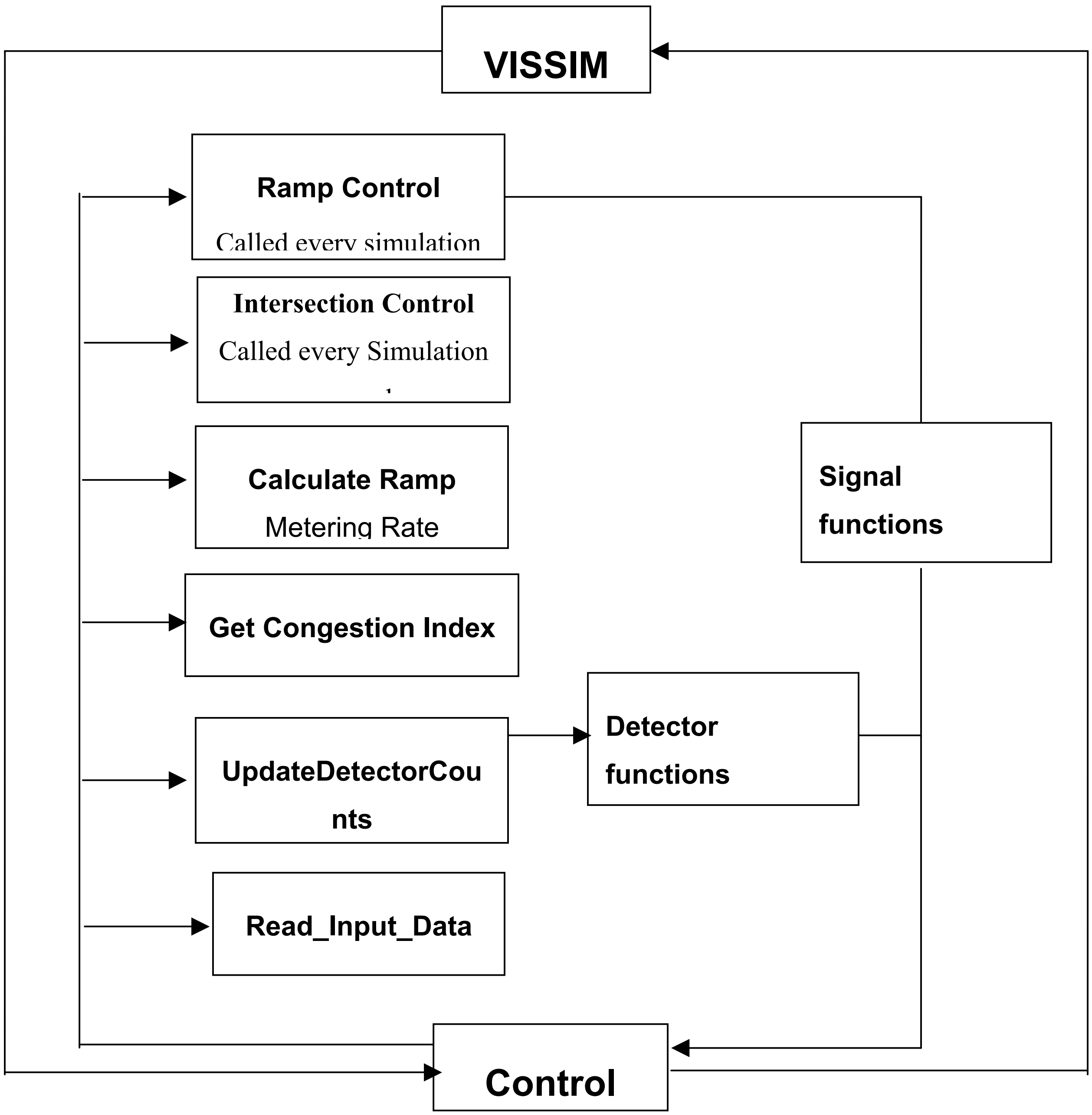


Figure 4.2.5 Simplified structure of the virtual controller for coordinated control

4.3 Evaluation of Adaptive Coordinated Control Strategies with an Example Network

The proposed adaptive coordination strategy was evaluated in a sample network located at the I-35W Northbound and Washington Ave. near downtown Minneapolis, Minnesota, using the microscopic simulation model VISSIM. Figure 4.3.1 shows the sample freeway entrance area modeled with VISSIM. The intersection in the sample network is currently operated in a pre-timed mode whose phase sequence is shown in Figure 4.3.2. For this evaluation, the proposed coordinated control method is coded into the virtual controller using the methodologies developed earlier in this study as shown in Figure 4.2.5.

The proposed adaptive coordinated control strategy is simulated with different demand patterns and its performance is compared with that of two non-coordinated control methods, i.e., no metering with pre-timed and no metering with actuated intersection control. Figure 4.3.2 also includes the minimum and maximum duration of each stage used for both actuated and adaptive intersection control. The maximum duration of each stage is used as the stage interval for the pre-timed intersection control. Figure 4.3.3 shows the different demand patterns used in this evaluation for arterials and freeways.

Figure 4.4.4 shows the evaluation results in terms of the estimated travel time of the left-turn vehicles in the sample network traveling from the upstream arterial boundary until the merging point of the main freeway after they pass the ramp meter. As shown in the figure, the adaptive coordinated control clearly produced the shorter left-turn travel time, indicating better coordination, than other methods that did not apply ramp metering. Further, as shown in Table 4.3.1, the proposed adaptive coordinated control produced consistently less total-vehicle hours with higher total vehicle-miles than other methods for same demand patterns. It needs to be pointed out that the advantage of the adaptive coordinated control became less obvious in terms of reducing travel time as congestion increases with heavy demand.

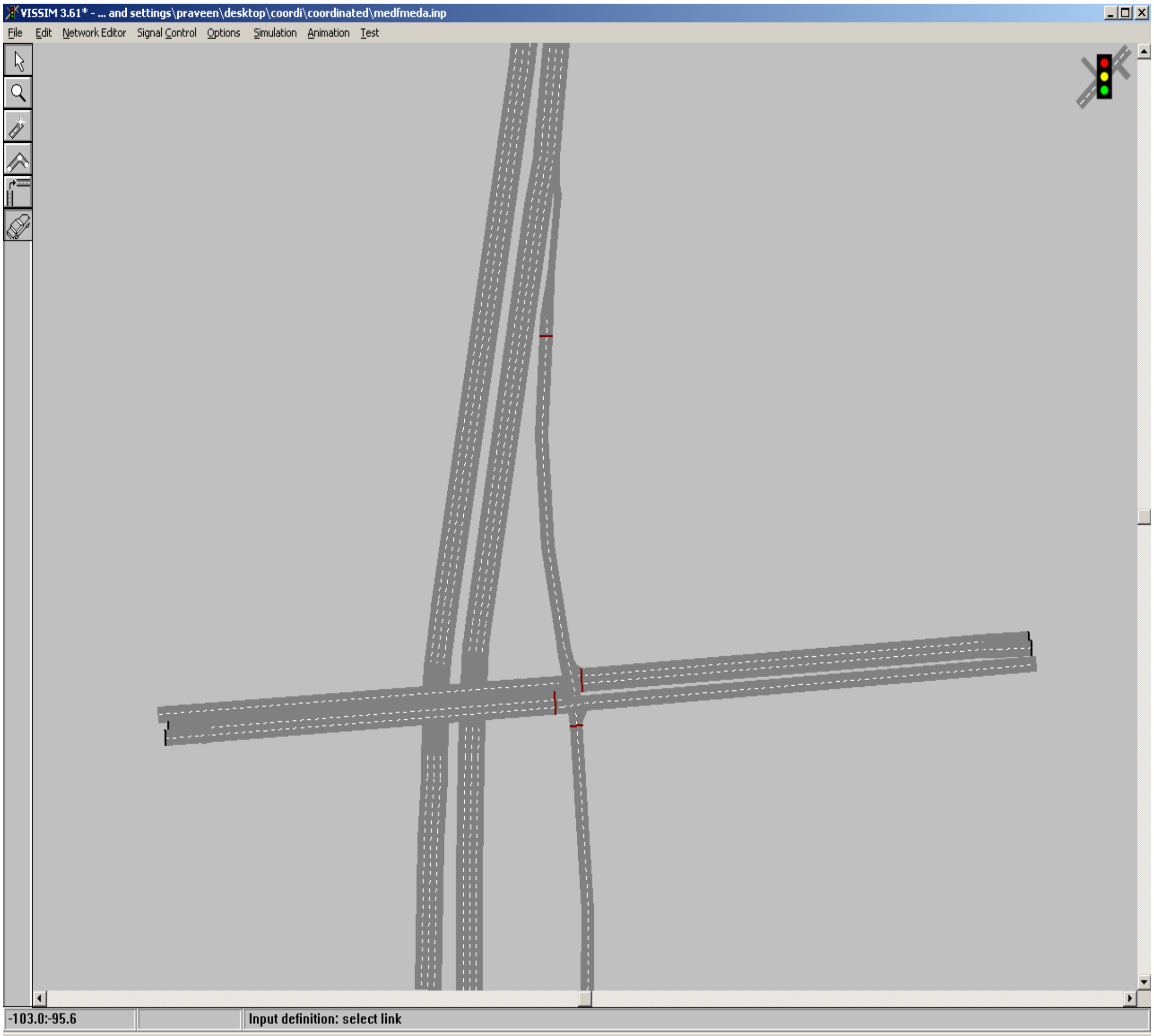


Figure 4.3.1 Sample intersection for testing coordinated control strategy (Washington Ave. at I-35W NB)

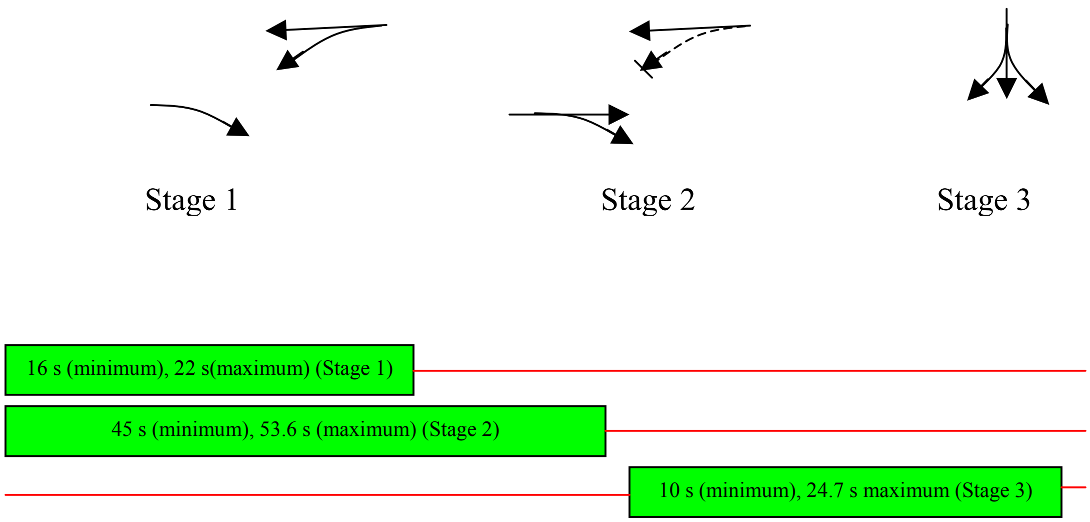
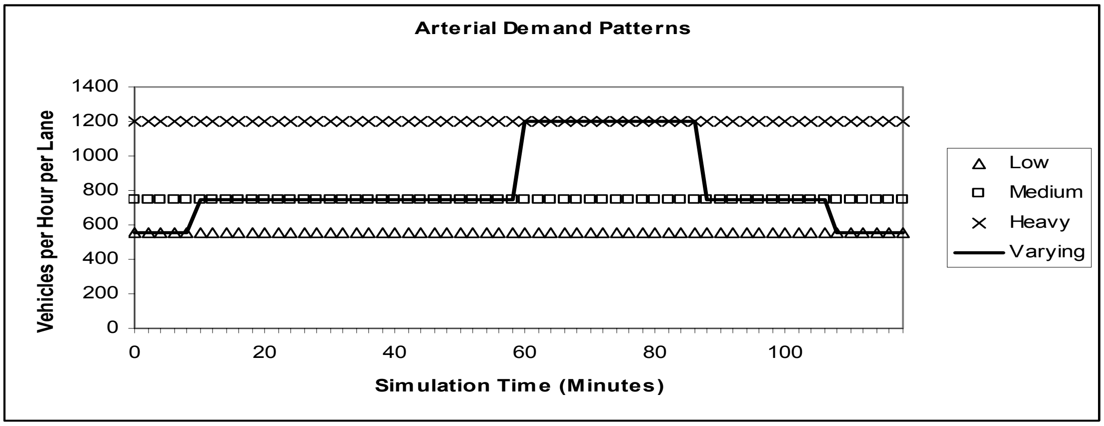


Figure 4.3.2 Timing Plans for Sample Intersection



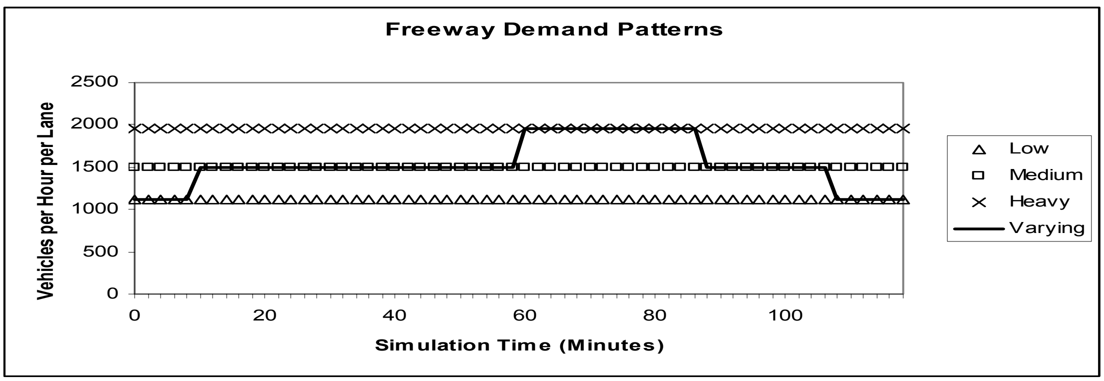
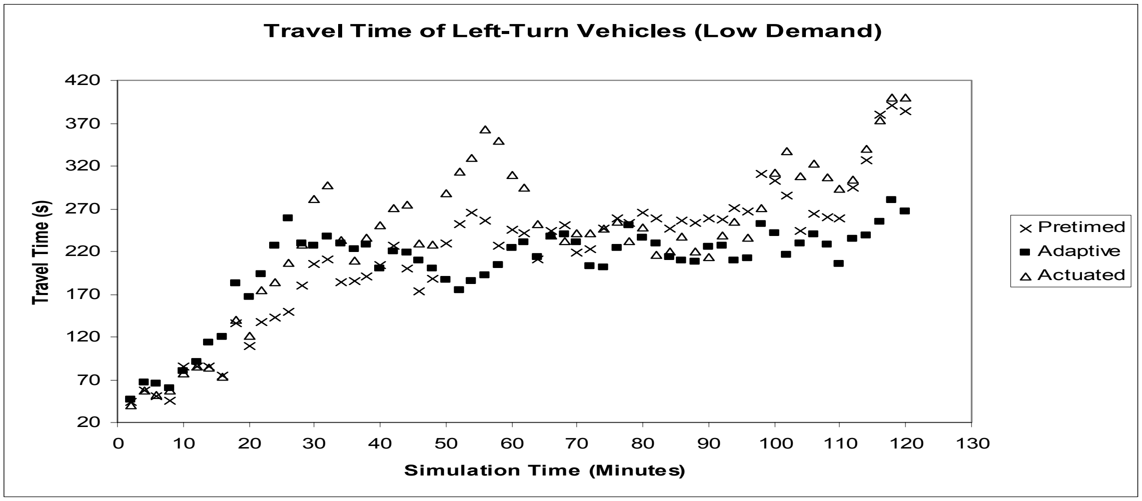
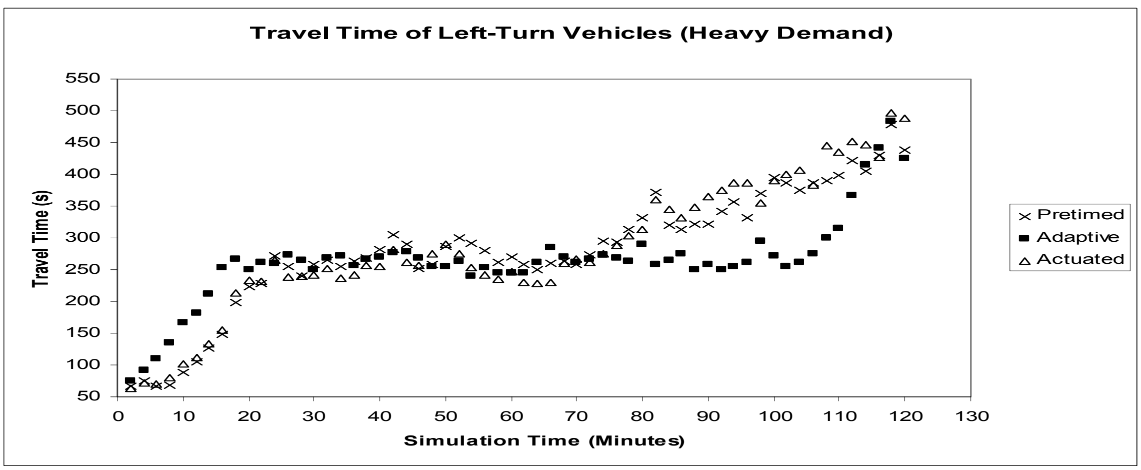


Figure 4.3.3 Demand patterns used for evaluation





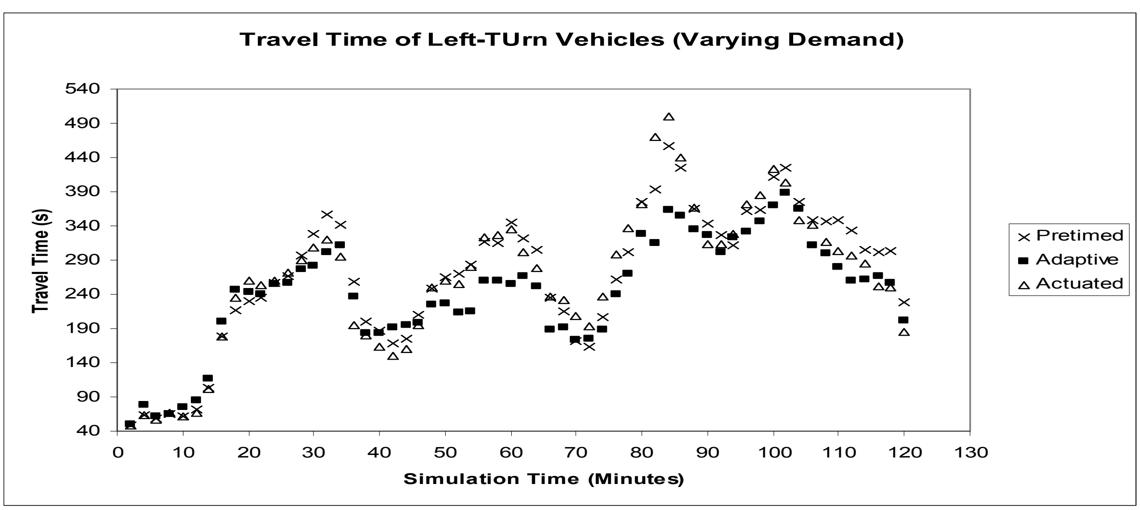


Figure 4.3.4 Estimated Travel Time for Left-Turn Vehicles

Table 4.3.1 Network-wide performance measures for each control option

		Low		Medium		Heavy		Varying	
		Veh-hrs	Veh-miles	Veh-hrs	Veh-miles	Veh-hrs	Veh-miles	Veh-hrs	Veh-miles
Random Seed 1	Pretimed/ Nometering	577	8622	880	9699	959	10213	593	8440
	Actuated/ Nometering	597	8589	880	9698	960	10212	601	8468
	Adaptive Coordinated	507	8600	869	9743	955	10269	569	8519
Random Seed 2	Pretimed/ Nometering	588	8593	894	9662	960	10203	618	8470
	Actuated/ Nometering	572	8595	892	9702	959	10223	613	8479
	Adaptive Coordinated	534	8597	880	9788	952	10223	574	8505
Random Seed 3	Pretimed/ Nometering	592	8562	888	9707	962	10223	602	8470
	Actuated/ Nometering	578	8615	890	9660	959	10235	610	8480
	Adaptive Coordinated	537	8592	879	9794	957	10238	572	8510

5. Conclusions and Future Research Needs

The major accomplishments of this research include 1) adaptation/application of a microscopic network simulation model for developing a testing environment for ramp metering and coordinated control strategies, 2) development of on/off-line virtual controllers to implement different types of control strategies with the microscopic simulation model, 3) simulation/ evaluation of the new Minnesota ramp metering algorithm using the corridor testing environment developed in this study, and finally 4) development/evaluation of a coordinated adaptive control strategy for a ramp-intersection area using the virtual controller-simulator environment. The example applications of the testing environment with the new ramp metering and adaptive coordinated control strategies demonstrated the effectiveness of the microscopic simulation model in evaluating the performance of various control methods prior to field implementation. The simulation of the new ramp metering algorithm has lead to the development of an alternative queue-management strategy in term of determining minimum metering rates.

The adaptive coordinated control strategy developed in this study tries to achieve the balanced operation for freeway and arterial traffic flows using a direct control approach with measurements, i.e., without employing conventional traffic models or optimal control methods. The adaptive metering module continuously adapts its control rule to the ever-changing traffic conditions, while the intersection module explicitly reflects the traffic condition at ramp area in determining signal phases. The evaluation results in a sample network with microscopic simulation show clear advantage of the proposed method in reducing the overall delay at the intersection area, while producing higher or compatible total vehicle-miles compared with the conventional control methods that do not employ ramp metering.

The corridor simulation environment developed in this study can be used for various types of future studies, which include the improvement of the ramp metering algorithm to take advantage of the maximum allowable waiting time at entrance ramps. The new metering strategy can identify current traffic patterns and determine/implement the best algorithm for a given traffic pattern under operational restrictions. Combining the adaptive intersection control with the current system-wide, stratified ramp metering algorithm needs to be conducted and evaluated with the simulation environment developed in this research. Field testing of the new adaptive coordinated control strategy can be also pursued starting with an isolated area.

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