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Development of a Simulation Model of an ITS Corridor

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Submitted by

Dr. Kaan Ozbay,* Ph.D.
Associate Professor

Bekir Bartin,* M.Sc.
Research Associate, M.Sc.

* Department of Civil & Environmental
Engineering
Rutgers, The State University of New Jersey

NJDOT Research Project Manager
Karl Brodtman

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16. Abstract

In this project, the South Jersey highway priority corridor is chosen as the evaluation network. From historical observations, it is well known that South Jersey highways have already reached high traffic congestion levels. This is especially evident during the morning peak hours due to the demand originating from Camden County destined to the Philadelphia business district. A detailed simulation model of the South Jersey highway network is developed using PARAMICS micro simulation software. Several Intelligent Transportation Systems (ITS) scenarios, such as vehicle routing using variable message signs and ramp metering, are evaluated. The cost/benefit analysis of these technologies is also performed based on the simulation results.

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EXECUTIVE SUMMARY

Intelligent transportation systems (ITS) aim to reduce the travel time of vehicles by controlling the existing transportation infrastructure using state-of-the-art technology. One of the current emphasis areas in ITS is improved coordination of existing, and future infrastructure to improve the safety and reliability of surface transportation systems as well as to be able to restore the transportation system to normalcy in the case of a disaster. Many ITS technologies, such as smart card technology, global positioning system (GPS) on cargo trucks, weigh stations, E-Z pass technology, traffic sensors, and wireless communication that are aimed to increase the efficiency of the transportation services can now be used to ensure the security of the surface transportation system in the event of unexpected emergencies.

Capital intensive solutions, such as capacity expansion by building new roads and politically controversial measures such as higher fuel taxes or congestion pricing proved to be relatively inefficient in addressing both long term and short term congestion problem effectively. Another approach involves using advanced technologies to increase the efficiency of the existing transportation system. ITS has thus emerged as a relatively inexpensive and easily implementable new solution to the traffic congestion problem.

The South Jersey highway priority corridor is chosen as the evaluation network in this project. From historical observations, it is well known that South Jersey highways have already reached high traffic congestion levels, especially during the morning peak hours due to the demand originating from Camden County destined to Philadelphia business district. A detailed simulation model of southern NJ highway network is modeled using PARAMICS micro simulation software. Several ITS scenarios, such as vehicle routing using variable message signs and ramp metering, are evaluated. The cost/benefit analysis of these technologies is also performed based on the simulation results.

INTRODUCTION

Traffic congestion has been a serious problem for the last few decades and has given rise to increased travel times, vehicle-operating costs and stress levels for drivers. Travel delay has also affected the cost of conducting business, both regarding logistics and higher wages paid to employees in compensation for long commutes (1). For example, commuters who work in New York often find themselves leaving several hours early to ensure on time arrival. A recent study conducted by the United States Department of Transportation (USDOT) Bureau of Statistics showed that the average daily person-hours of delay in 1994 for the New York Metropolitan area was 2,162,000 hours, compared to 1,310,000 hours in 1982 (44). This statistic simply indicates that the delay experienced by citizens of this region is excessive. The economic impact of this statistic is very significant, as well. The same study found that the congestion cost per capita exceeded $500 in the same region. Congestion costs per capita reflects the amount of money lost by each individual per year due to congestion, either in delay, damage to the roadway, or other factors. Traffic congestion has also plagued the society and the government with exorbitant indirect costs of air pollution and noise, as well as direct costs due to capital expenses.

Over the years, the problem has been addressed by various attempts such as:

- Capacity expansion
- Higher fuel and vehicle registration taxes
- Congestion pricing
- Expansion of mass transit, car-pooling
- Increased traffic management and operations

None of these approaches could manage to fully overcome the congestion problem. Especially capital intensive solutions, such as capacity expansion by building new roads, and politically controversial measures, such as higher fuel taxes and congestion pricing, proved to be relatively inefficient in addressing both long term and short term congestion problems effectively. Another approach involves using advanced technologies to increase the efficiency of the existing transportation system. ITS has thus emerged as a relatively inexpensive and easily implementable new solution to the traffic congestion problem.

What is ITS?

"ITS is the integration of users, transport systems and vehicles through the state-of-the-art information and communication systems to improve the efficiency and safety of transportation systems" (14). ITS applications include freeway management, incident management, electronic toll collection, real-time traveler information, freeway management, transit management, traffic signal control, and railroad crossings. Since ITS became official in 1991, USDOT reported the received benefits of ITS applications in the nation as follows (43):

- Advanced traffic surveillance and signal control systems have resulted in travel time improvements ranging from 8% to 25%.
- Freeway management systems, primarily through ramp metering, have reduced crashes by 24% to 50% while handling 8% to 22% more traffic at speeds 13% to 48% faster than pre-existing congested conditions.
- Electronic fare payment technologies for transit systems have resulted in increased revenues of 3% to 30% due to fewer evasions.
- Incident management programs can reduce delay associated with congestion caused by incidents by 10% to 45%.
- Electronic toll collection increases capacity by 200% to 300% compared with attended lanes.

Motivation

This project was initiated by New Jersey Department of Transportation (NJDOT) to evaluate the impacts of ITS technologies in the South Jersey (SJ) highway priority corridor.

New Jersey is strategically located between New York City and Philadelphia, the nation's first and fourth largest cities. Because of its apparent role in and proximity to the strong markets and population centers, New Jersey has also nation's one of the busiest transportation systems. As in any major metropolitan area, traffic congestion has a significant impact on the community and businesses in New Jersey (NJ). The key objective of this project is to evaluate the candidate ITS components for efficiency, applicability, and overall benefits.

In fact, various ITS technologies are currently being implemented along several priority corridors in New Jersey. Many new ITS technologies are also under consideration. However, experience shows that it is generally very difficult or sometimes impossible to accurately predict the impacts and benefits of these technologies before they are actually implemented in a specific environment. The most difficult task is to choose the set of ITS technologies that will create the most benefits for the users of the transportation system.

The right selection of the most useful ITS technologies is very important for two major reasons:

1. First, the budget for acquiring and implementing new ITS technologies is still relatively small. It is very important to spend scarce resources the best way possible. Thus, investing in ITS technology that will only produce marginal benefits can have long-term negative effects on the overall efficiency of the transportation network.
2. Second, ITS is still a new area. Implementation of an ITS technology that does not perform effectively can have long term effects on the acceptance of these technologies by the public and policy makers.

It is thus clear that dependable tools are needed for selecting the best ITS technologies for deployment. However, this is not as straight forward as building a new road. The capacity increase resulting from the construction of new lane-miles is easy to understand and estimate. It is not, however, so easy to quantify the additional benefits of advanced traveler information systems (ATIS) and advanced traffic management systems (ATMS). It is a non-trivial task to estimate the capacity increase on a freeway resulting from the implementation of ATMS technologies, such as ramp metering and variable message signs used for traffic diversion during incidents. Moreover, these ITS technologies have wider effects beyond the highway section at which they are implemented. For example, ramp metering effectively coordinated with arterial signals can relieve congestion on the freeways as well as on local roads. On the other hand, queue spill over onto the arterial street as a result of ramp metering, can create unexpected congestion on the local roads. Thus, it is not affordable to deploy ITS technologies to later find out that they do not work as hoped. It is very important to predict their impact on the traffic before actually spending millions of dollars for deployment.

The question then is how to choose the ITS technologies best suited for the study priority corridor in New Jersey. The answer lies in the development of a high fidelity simulation laboratory environment for testing the success of ITS technologies in this high priority corridor. ITS technologies have to be evaluated for their impact on the time-dependent dynamics of traffic flow and demand. Microscopic traffic simulation is the only way to capture the dynamic nature of traffic flow and demand within a certain time interval. This project thus develops a detailed simulation model of the SJ ITS priority corridor to test and assess the impacts of different ITS technologies on traffic flow and demand before they are deployed. This simulation model is a laboratory that can be used now and in the future to assess the impacts of any ITS technology quickly and inexpensively.

Study Area

The SJ highway priority corridor is chosen as the evaluation network in this project. From historical observations, it is well known that SJ highways have already reached high traffic congestion levels, especially during the morning peak hours due to the demand originating from Camden County destined to Philadelphia business district.

Project Objectives

The main objectives of this project are:

1. To develop and calibrate / validate a high fidelity simulation model of the selected ITS corridor in New Jersey: This simulation model is developed using PARAMICS simulation tool. It is very important to obtain the appropriate data that will be used to calibrate the simulation model. Without accurate calibration of the developed simulation model of the selected priority corridor, the second objective of this project cannot be accomplished successfully.

2. To evaluate the effectiveness of existing and planned ITS technologies in the selected ITS priority corridor: This objective is accomplished by using the calibrated simulation model. An important aspect is selecting ITS technologies to be evaluated, as well as determining the “Measures of Effectiveness (MOE)” to be employed by the evaluation process.

Candidate ITS technologies

Based on a recent study conducted for NJDOT by Parson Brinkerhoff (39) the ITS applications that are suggested for this priority corridor are:

- Vehicle routing via variable message signs
- Advanced traffic management via ramp metering

Figure 1 illustrates the suggested locations of these candidate technologies in the SJ priority corridor. Alternative scenarios including different combinations of these applications are tested with and without incidents and evaluated based on selected MOEs. The selected locations of the ITS application scenarios in this project are based on (39)

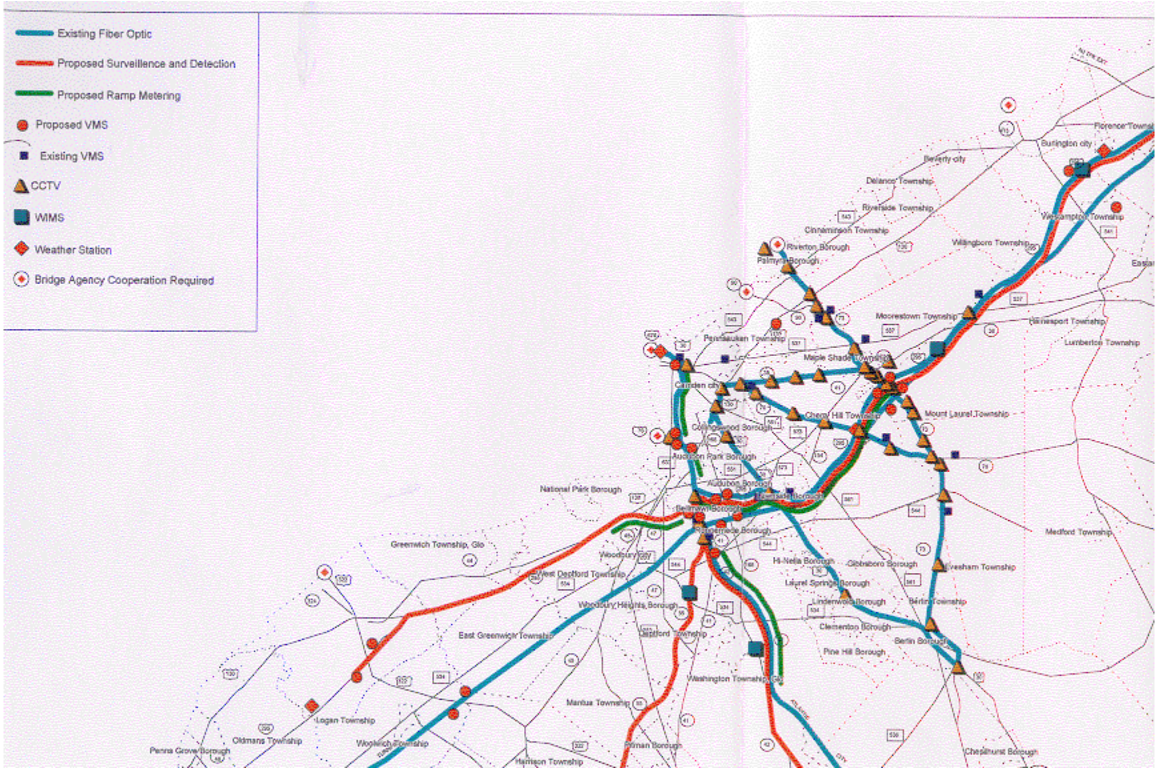


Figure 1. Suggested locations for the candidate ITS technologies

Measure of Effectiveness

After the simulation model is developed, calibrated, and finally validated, it is important to determine how the selected ITS technologies are evaluated. In this study, we propose to quantify the effects of ITS technologies using various MOE. The measures that are considered in this study are:

1. Total travel time in the network
2. Origin destination (O-D) travel times

The framework shown in Figure 2 is used to evaluate alternative ITS technologies for the SJ network. The MOEs are measured using the simulation. After determining MOEs, the next step is to use an appropriate methodology for evaluation. The use of cost / benefit analysis is proposed for performing the final step of evaluation. The deployment of each ITS technology has a monetary cost associated with it. On the other hand, the benefits of these ITS technologies are quantified in the MOEs described above. The task is thereafter is to associate a real cost with each MOE. These MOEs can easily be reflected as dollar savings using unit cost values as presented in the literature.

After the costs and benefits are determined, a cost / benefit analysis for different ITS technologies is performed to determine the best possible alternatives.

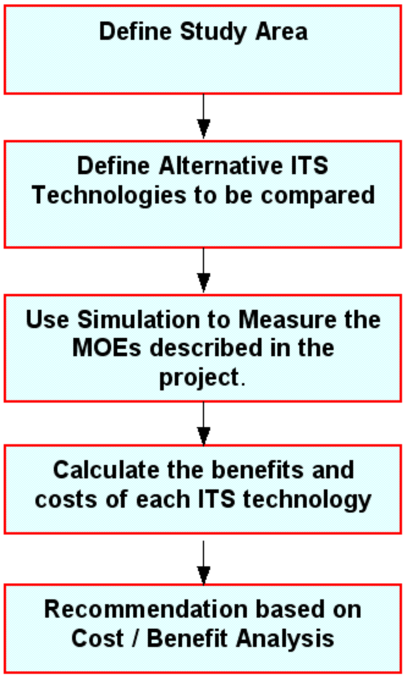


Figure 2. Proposed evaluation methodology

In the next section, a detailed explanation of the simulation model development is presented. Subsequent chapters are dedicated to the description of the candidate ITS technologies, and how they are modeled and simulated in PARAMICS simulation software. Section 3 is dedicated to the simulation analyses of variable message sign (VMS) route guidance in the study network. Section 4 describes the ramp metering technologies considered in this study and presents the simulation of ramp metering in the study network. It also describes alternative scenarios of their applications, and presents evaluation results. Section 5 presents cost / benefit analyses of the alternative scenarios.

NETWORK MODEL DEVELOPMENT

Deploying a reliable ITS technology is a non-trivial task, and certainly not inexpensive. Its development requires the resolution of several theoretical, technical and practical issues, which will be addressed throughout the study. The widespread belief is that these issues involved highly influence credibility with the drivers, and thus the effectiveness of the overall system (45). It is therefore crucial to understand the current network characteristics, and predict the likely impact of the desired system under various demand and network conditions before actually implementing in a priority corridor. In this context, computer simulation is a very helpful offline tool for testing the proposed system before implementation. It is clearly a cheaper and quicker way to analyze the effectiveness and the potential benefits of the proposed system.

This chapter deals with the development of the ITS priority corridor simulation model using the selected microscopic simulation tool, namely PARAMICS. PARAMICS is a suite of high performance software tools for microscopic traffic simulation. Individual vehicles are modeled in fine detail for the duration of their entire trip, providing accurate traffic flow, transit time and congestion information, as well as enabling the modeling of the interface between drivers and ITS (1). Besides being a microscopic traffic simulator, PARAMICS has stronger motivating features over other existing traffic simulation tools:

- Excellence in modeling highly congested networks and ITS infrastructures
- Advanced vehicle-following and lane-changing behavior
- Capability of incorporating driver and vehicle performance parameters
- Batch mode operations for statistical studies
- Application Programming Interface (API) option, which enables users to modify the simulation routine for testing their own models

The highway network model generated for simulation purposes should closely represent the actual network characteristics. Network characteristics can be grouped in three, namely:

- Network Components, including links, intersections, interchanges, ramps, zones, etc.

- Geometric aspects and limitations, including accurate representation of roadway alignment, gradient, number of lanes, lane width, speed limits, signposting distances, stop signs, visibility, one-way roads, right and left turn lanes, etc.
- O-D demands, including the demand between each O-D pair for a given time period.

Comprehensive modeling of network components with accurate geometric features is essential for the continuity of traffic flow in the network. The O-D demand matrix is used to generate traffic flows in the model network. Obtaining correct O-D demands is very important to ensure valid traffic flows in the network model. It is well known by researchers that even a minor flaw in modeling may lead to an inaccurate representation of the actual network characteristics. Therefore, utmost attention should be spent to ensure the development of an appropriately calibrated and validated network model.

Building Network Characteristics

The network used for simulation purposes is extracted from the main network given in Figure 3. This network is extracted from the US network available in ArcView GIS software data files. The area under consideration is approximately 90 square miles. Only major highways and freeways are included in the model, whereas the secondary roadways are modeled as demand connectors to the major highways.

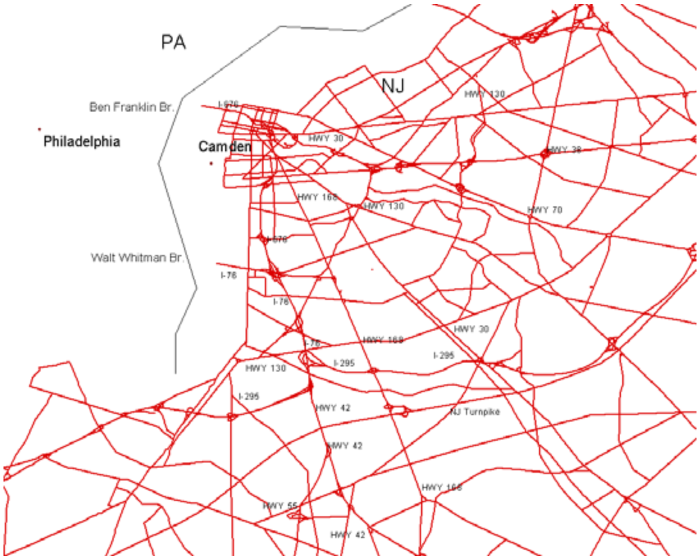


Figure 3. South Jersey highway network

The following are the steps performed to model the SJ highway network in PARAMICS.

Selection of Overlay

Detailed network layout is loaded directly into PARAMICS. This overlay is used as a template to build the network model. The scale of the overlay file is generally not consistent with the scale of PARAMICS network. It is crucial that the scale of the overlay and the actual network match. Otherwise, this would produce irrevocable mistakes later in the validation step due to inaccurate distances. The scale adjustment is conducted simply by taking a reference link and changing the scale of the overlay till the selected link's distance matches with its real distance. Figure 3 is used as an overlay in this study.

Skeleton Network Coding

A skeleton network defines the position of the nodes and links in the network model. First, it is ensured that the node positions match the overlay intersections. Then simply by connecting the nodes, the skeleton network model is developed. This step also contains most of the meticulous work for modeling geometric aspects of the network model such as roadway alignment, drawing curves, interchanges, on and off-ramps, highway merging, etc. A close view of the interchange of I-76 and US HWY 130 is demonstrated in Figure 4.

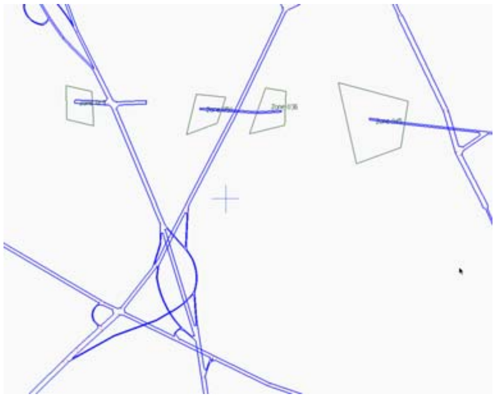


Figure 4. A major interchange of SJ Network modeled PARAMICS

Detailed Network Coding

This step involves coding the remaining geometric aspects and limitations of the highway network, such as number of lanes, highway type, speed limit, and line width, etc. This information is gathered in several site visits, as well as by using the available resources online. In this study, the information given in “NJDOT Straight Line Diagrams” is utilized.

O-D Demands

SJ – Philadelphia highway travel demand matrices for different time periods of the day and the corresponding zone locations are generated using the data provided by theDelaware Valley Region Planning Committee (DVRPC). The zone locations are represented with red dots in Figure 5.

There were two problems with the original O-D demand file provided by DVRPC. First, the demand matrix is not easy to integrate into the PARAMICS demand file. The size of the original demand matrix is 1626 x 1626. The network characteristics are stored using text files in PARAMICS. Hence, the demand file must be stored in a text file format. However, it is not possible to store the demand row with 1626 numbers in a text file. This is higher than the allowable size in a text file format. Secondly, even if the demand matrix were integrated with PARAMICS, locating and drawing all 1626 zones would be a meticulous and an almost impossible task given the rather limited scope of this study. The demand matrix is therefore aggregated in a way that the zones that lie outside the network (external zones) form a lower number of combined zones. Whereas, the internal zones are used as they originally appear in the actual network.

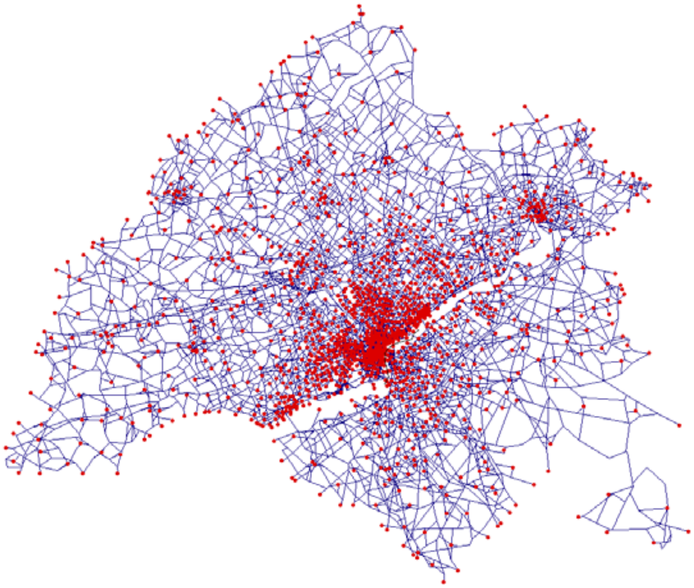


Figure 5. Demand zones in Philadelphia-SJ area

As for the aggregated zones, there are 33 external aggregated zones on the South Jersey side and 2 external aggregated zones on the Philadelphia side (one for each bridge). Aggregating the zones resulted in a smaller demand matrix of a size of 137 x 137, which can easily be integrated into PARAMICS. The same analysis is repeated and aggregated travel demand matrices are obtained for other time periods.

Once the aggregated travel demand matrices are obtained, the next task was to draw zone boundaries in PARAMICS. *Internal zones* are connected to the network by major and minor arterials or local roads. Whereas, *external zones* are connected by major highways since the demand is relatively higher due to the demand aggregation. Figure 6 shows the screenshot of the modeled PARAMICS highway network with the aggregated zone structure.

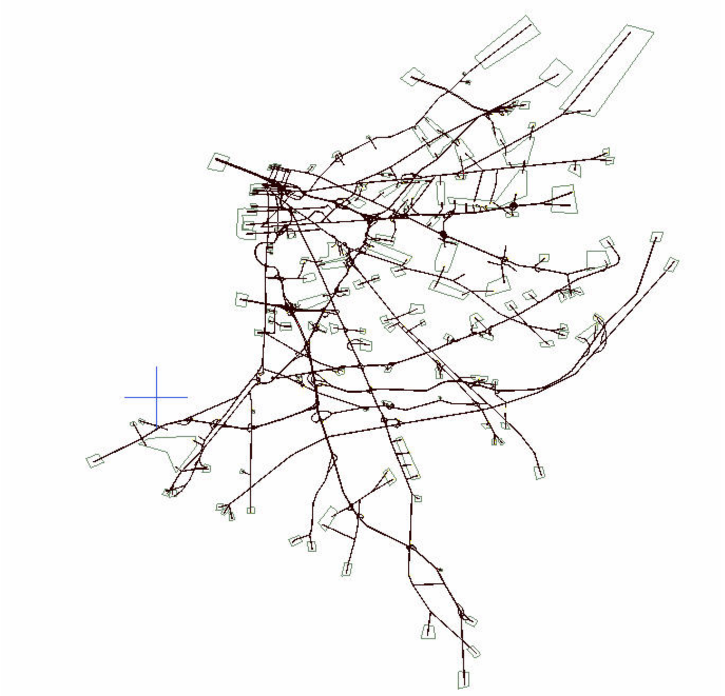


Figure 6. Highway network modeled in PARAMICS

Model Calibration

After establishing network characteristics calibration is the next step in model development. Calibration is the modification process of the initial model input parameters to obtain the actual traffic characteristics in the network as represented by various network outputs. Model input parameters vary for each simulation tool, but in general include driver characteristics, mean headway, mean reaction time, route cost equations, etc. Network outputs usually include measures such as vehicle counts, mean speed, route travel time, etc. 3 level calibration / validation process is employed (Although the model calibration process elucidated here is PARAMICS specific, the steps followed are quite general and applicable in different simulation tools.

Pre-Calibration Step

Most model calibration steps presume that the model network characteristics and the O-D demand tables are accurate. A great deal of effort is spent to change model input parameters and make necessary modifications in the demand matrix. However, since only a subset of the actual network is modeled here, the demand specified by the O-D matrix is higher than what the modeled network supply can handle. Due to the absence of some or all the links connecting specific zones in the network model, the traffic demand will resort to using the available routes. This results in excess traffic flow on the links. Hence, the zones of this type should be detected in the network model, and the demand between them has to be adjusted accordingly. Various simulation runs are performed to verify that the simulation model produces reasonable results given the modeled network characteristics. This is the step before the calibration and validation of the simulation model and is meant to check if the simulation is working properly, and eliminate obvious errors.

Model Calibration/Validation

As it is well known by researchers who deal with network calibration, there are no specific guidelines on how to carry out this task. This is a trial-and-error process and requires a great deal of computational effort and time. However, the most common method suggested by many researchers is to start with a lower percentage of the actual demand matrix, and to gradually increase the demand while correcting the problems as they occur. In addition to the conventional steps of model calibration, the O-D demand matrix is adjusted based on network outputs in this study.

Multiple simulation runs were performed with different values of the input parameters described above. A suggested method is to observe the effect of each parameter while fixing the other parameter values. There are several model input parameters in PARAMICS that highly affect the traffic characteristics (37):

Generalized cost coefficients

Travel costs represent a combination of factors that drivers take into account when choosing routes. Time and distance are used in calculating travel costs in PARAMICS. Coefficients of time and distance control the perceived travel costs of drivers and changing these affect the route choice of drivers. In this study, default values for these coefficients are utilized. Namely, drivers make their route choices based on travel time only.

Feedback period

There are 3 different assignment rules in PARAMICS: All-or-nothing, stochastic assignment and dynamic feedback assignment. *All-or-nothing* assignment assumes that all drivers between O-D pairs choose the same route and that the link costs do not depend on traffic flow levels. *Stochastic assignment* method tries to account for variability in travel costs. It assumes that the travel costs are perceived by drivers randomly within predefined limits. Dynamic feedback assignment assumes that drivers who are familiar with the network change their routes if any information on their routes is fed back to them. Route costs are calculated automatically by PARAMICS at every predefined time period. The value of the feedback period affects traffic flow patterns considerably. In our calibration process, a feedback period of 6 minutes has been found to give better results.

Perturbation percentages

In stochastic assignment, the randomness in travel costs perceived by drivers is defined by two factors: *perturbation algorithm* and *perturbation value*. There are two perturbation algorithms: percentage and square root algorithms. Here, percentage algorithm is preferred, because the square root algorithm is insensitive to perturbation and seems very rigid in its route choice. Perturbation value defines the percentage of vehicles subject to perturbation in their route choice.

When dealing with very large networks, especially with a combination of urban and highway trips, using separate assignment methods is an effective solution in the calibration process. The three assignment rules can be used together in PARAMICS. For example, between zones those are far apart and connected with freeways, for a certain percentage of trips, stochastic assignment is more applicable. Determining this percentage is a part of the calibration process. On the other hand, dynamic feedback assignment is more effective for local trips that are relatively shorter in distance.

Driver characteristics

Two driver characteristics affect calibration results: *familiarity*, *aggression* and *awareness*. Familiarity percentage of drivers affects the number of vehicles that will change their route choice based on the feedback information. In the calibration process, 85 % familiarity of vehicles yielded better results. Also, aggression and awareness define if the driver is aware of the surroundings, make quick decisions, change lanes quickly, etc, which all affect traffic characteristics.

Mean headway and reaction time

The values for mean headway and reaction time have enormous effects on the link capacities, and hence on the overall traffic characteristics. The best values for these parameters can only be obtained after several network runs. The headway value usually varies between 0.5 seconds and 2.5 seconds, and the reaction time between 0.2 and 2 seconds. In the network runs, a mean headway of 0.7 seconds and a mean reaction time of 0.5 seconds have been observed to be the most effective.

Signposting

PARAMICS automatically generates signposts for various network features, such as diverge, merge, on-off ramps, etc. Two parameters are accompanied with signposts: *signposting dist*ance and *decision distance*. The former value defines the distance between the signpost and the network feature. The latter value defines the distance over which vehicles make their lane changes. It has been observed that incorrect values for these parameters result in breakdown of traffic at these links. Hence, all signpost distance should be checked in the network to obtain a smooth traffic flow.

The effect of each parameter value is determined by observing network outputs. In the calibration runs here, only vehicle counts are utilized as network outputs. The data sources of vehicle counts are:

- NJDOT online data resources (29)
- Ground truth data for the SJ network (along I-76 and I-676 at 5 different locations for PM period)

NJDOT vehicle count data include AADT values for various highways in NJ. These counts have been converted into minute-by-minute counts assuming a peak hour factor in the range of 8% to12%. This range is shown as minimum and maximum bounds for our simulation counts. PARAMICS enables users to collect link statistics with the use of loop detectors. 32 loop detectors are placed throughout the modeled network to collect vehicle count statistics. These detectors are located in the model network at the analogous locations where NJDOT vehicle counts have been performed. Table 1 shows the comparison of the ground truth data and the data gathered by various simulation runs. The last 5 vehicle counts were collected by the Rutgers Team during October 2001 using video recording. The collected surveillance tapes were then processed using the image-processing unit in Rutgers Intelligent Transportation Systems Laboratory.

Table 1. Comparison of ground truth data and simulation results

Calibration Results of South Jersey Highway Network				
Location Number	*Highway Name*	*Simulation Counts*	*Ground Truth*	
			Min	Max
1	River Rd	36.56	13.93	20.90
2	Hwy 168	17.12	23.49	35.24
3		23.80	27.27	40.90
4		53.76	34.37	51.56
5		50.50	27.81	41.72
6		50.21	34.29	51.44
7	I-295	87.43	89.33	134.0
8		87.48	86.03	129.05
9		128.7	138.50	207.75
10		138.25	156.31	234.46
11		142.50	129.06	193.59
12	Hwy 130	56.50	37.93	56.90
13		56.73	35.35	53.02
14		75.49	51.25	76.88
15	Hwy 30	94.91	75.41	113.11
16		99.57	93.06	139.59
17		54.44	13.21	19.82
18		27.77	29.17	43.76
19	Hwy 70	59.62	57.59	86.39
20		57.92	63.74	95.60
21		54.48	61.27	91.90
22		51.55	72.04	108.06
23	Hwy 38	107.78	110.10	165.14
24		59.17	61.17	91.76
25		38.91	68.42	102.63

Table 1 Continued

26	Federal St	19.68	8.48	12.72
27		14.52	14.96	22.44
28	I-76 & I-676	94.26	75	100
29		87.50	67.2	85.4
30		80.61	67.6	85.6
31		36.70	26.6	34.8
32		32.75	19.8	27.4

It is seen from Table 1 that the vehicle counts collected from the simulation runs and the actual ground truth data are very much in accordance. Although only 33% of the vehicle counts fall in the range given by NJDOT vehicle counts, overall the numbers are sufficiently close to validate the calibrated simulation model.

To reinforce the validity of the calibration process, the travel times collected by the Rutgers Team along the I-76 and I-676 are also compared with the travel times obtained from the simulation model. Table 2 presents the statistical analyses of these two data sets.

Table 2. Travel time differences between ground truth and simulation model

	1st Run	2nd Run
Date of Observation	02/21/02	02/21/02
Sample Size	8	8
Average of Differences in Actual and Simulated Travel Time	-0.0145	0.0383
Standard Deviation of Differences	0.56	0.484
Calculated t-value	-0.0734	0.224
t-value read from the chart (95 % Confidence Interval)	-2.365	2.365
Significant	Yes	Yes

Although the simulation network model can be calibrated based on different model outputs, as mentioned earlier, in the case of a highway network as wide as this study's priority corridor it is often difficult to obtain such detailed data. Therefore, this study is limited to traffic counts only. Table 1 shows that the results of the calibration process are sufficient to simulate the proposed ITS technologies

VEHICLE ROUTING USING VARIABLE MESSAGE SIGNS

This chapter presents a micro simulation based methodology to evaluate the potential benefits of ITS technologies, more specifically of advanced traveler information systems (AITS) via variable message signs (VMS) in the SJ highway network.

ATIS stems from this basic need of drivers, as well as from the need of government agencies in increasing the efficiency of highway networks. For the individual, using ATIS can lead to more efficient travel choices and help reduce anxiety and stress associated with travel planning, way-finding and navigating through the network (Adler and Blue, 1998). For the system as a whole, if enough travelers use ATIS there will be significant reduction in travel time, fuel consumption, environmental costs (air pollution and noise), roadway safety (reduced number of incidents due to less workload on drivers), decrease in wear-tear of the highway infrastructure system. In fact, among all these benefits, the reduced travel time objective appears as the key element of all of the highway system management issues. It is clear that the rest of the above listed benefits are due to the reduced travel times. Excess travel times occur because of the limited alternative routes known by drivers or inaccurate perception of the known ones. ATIS aims at informing drivers to achieve an efficiently operating highway transportation system in terms of reduced travel time.

ATIS emerged as a popular traffic management strategy as a result of the improvements in computer and communication technologies. It attempts to efficiently utilize the advanced communication technologies to disseminate information to travelers. Adler and Blue (2) divide the ATIS application in two categories based on its evolution. **First generation** of ATIS, which is designed to improve flow at certain points in the network, or to make travelers aware of non-recurring congestion. Variable message signs (VMS) and highway advisory radios are representatives of the **first generation** systems. Most of these applications concern with hazard waning and speed advice. **Second generation** of ATIS include a wider range of technology to provide personalized real-time information and two-way communication with travelers. The application of this technology requires an in-vehicle navigation device designed for this purpose. The representatives of this category can be listed as interactive user interface, vehicle location and intelligent mapping, individual path search, yellow pages directory, and dynamic route guidance (2).

The development of the latter one is a non-trivial task, and currently being deployed as a part of evaluation projects. TravTek, ADVANCE, Pathfinder, FAST-TRAC, DRIVE, PROMETHEUS, RACS, AMTICS are the examples of some projects undertaken worldwide to develop in-vehicle route guidance systems (IVRG).

The success of ATIS depends on several factors, such as correct understanding of the drivers' routing decisions, drivers' compliance rate, reliability of the provided information, accurate percentage of equipped vehicles, etc. Numerous studies in the literature dealt with the understanding and solving such problems. Routing decisions, how drivers utilize the available highway infrastructure have always been an interest of researchers. Batley and Clegg (5) investigated how drivers change their decisions on route and departure times with the changes in the network conditions, using on-street survey evidence. Chen et al.(7) looked at the various traffic assignment models and evaluated each method and their effect on travel time reliability in a network where demand and supply may vary. Mahmassani (24) evaluates different traffic assignment rules with a simulation tool. (25, 4, 16, 41, 13, 31) looked at the driver behavior, learning, and changes in preferences in response to ATIS. Watling and van Vuren (46) provide a detailed overview of modeling issues, as well as the issues that are crucial in achieving the desired efficiency of dynamic route guidance systems.

As it is mentioned earlier, it is very important to understand the impact of ATIS on the traffic of the study area before its actual implementation, yet it is not straightforward to estimate the impacts of this new technology. Hence, high-fidelity simulation software is required to assess the impacts of the ATIS technology in a quick and inexpensive way. The previous chapter developed a detailed simulation model of SJ highway network.

This simulation model will be a laboratory to assess the impact of VMS routing in the study area.

The first step of analysis is the determination of the possible VMS locations that will be tested using simulation model. In order to best evaluate the impact of VMS in the study area, realistic VMS locations that will maximize the opportunity of drivers' decision making should be determined. The suggestions of a recent technical memorandum by *Parsons Brinckerhoff*'s for NJDOT are used to determine the suitable VMS locations in the study area (39). In this report, the screening of the candidate VMS network is based on NJDOT policy and criteria regarding the placement of VMS sign structures to evaluate both need and location.

The second step is to incorporate the VMS routing algorithm in the simulation using the API feature of PARAMICS and obtain results for each scenario. This is accomplished by changing the underlying simulation routine of PARAMICS but will not be explained in detail here.

The third step of the proposed methodology is the comparison of the MOEs obtained for the tested scenarios and discussion of the benefits of the VMS-based traveler information dissemination.

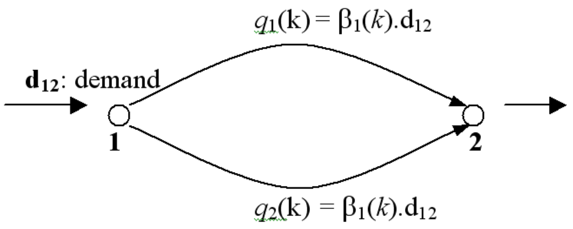
Simulation Analyses of Traffic Routing via VMS for the Model Network

The idea behind route guidance is to instruct drivers in such a way that the system performance is optimized. However, current real-world applications mainly focus on the dissemination of accident and congestion information to the drivers so that they can avoid those bottlenecks. More sophisticated systems attempt to also give advisory information on the best alternative route(s) given the prevailing network conditions. The underlying decisive factor for a best route is often finding the shortest one (minimum travel time) to the destination. However, the challenge in a dynamic route guidance model is updating the information for each predetermined time interval based on the current traffic conditions (i.e. traffic volume at each link) in the network.

Numerous studies in the literature deal with effective VMS routing based on different control algorithms (6,10, 17,34). However, in the analyses presented here, the current deployment strategy adopted by traffic operations centers in reality are evaluated. According to this widely used traffic control strategy, if a route is congested (either due to recurrent or non-recurrent congestion) drivers are alerted to divert to alternative routes. Clearly, sophisticated routing and control algorithms can be used to improve the efficiency of these messages, but the goal of this paper is to evaluate the effectiveness of the current state-of-the-practice. After all most of these algorithms are not ready for full deployment for real-world applications.

Simulation Study

To evaluate the effectiveness of traveler information using simulation, we utilize a simple feedback type approach (Bang-Bang control) proposed by (35). This type of control is designed to minimize the difference between travel times of alternative routes j and the main route M simply by diverting vehicles from the main route to one of the uncongested routes, if $T_M - t_j \geq T_{\min}$, where $T_{\min}$ stand for the minimum acceptable delay. In an example network as in Figure 7, the objective of Bang-Bang Controller is to change $\beta_1(k)$ between 0 and 1 so that the travel time difference between two routes approaches 0.



$$\Delta t_{1-2}(k) > 0 \Rightarrow \beta_1(k) = 0$$
$$\Delta t_{1-2}(k) < 0 \Rightarrow \beta_1(k) = 1$$

Figure 7. A single origin-destination network

This process requires the real-time knowledge of travel times on each alternate route, and the main route at each time interval. Although the estimation of travel times for each alternative route is a fairly straightforward task in simulation, this process requires complete surveillance of these routes in reality. Indeed, the implementation of such a system itself leads to several other practical and theoretical problems (i.e. establishing power and communication connections to the infrastructure, data collection frequency, estimation algorithm). In our analyses, we assume that travel time estimation at each time period is accurate enough to implement the feedback control law mentioned above.

As vehicles traverse the diversion link characteristics of each vehicle are extracted (i.e. origin, destination, speed, driver characteristics, etc). If the vehicle is destined to the predefined zone, the program automatically checks the last updated route travel times. If $T_M - t_j \geq T_{\min}$ for any alternative route, then it determines if the vehicle follows routing information. This scanning process on control links is performed every time step. Vehicles accept /decline VMS routing based on the following driver's characteristics (38):

- Aggression: There are two types of drivers. First are the active drivers who tend to look for a quicker route and are therefore most likely to follow VMS advice. Second are the passive drivers who least likely to follow the guidance.
- Awareness: It is assumed that if the driver is unaware of the surroundings, he or she may not even see the displayed VMS information.
- Patience: It is also assumed that avoiding the additional delay is the major motivator of drivers who follow the VMS advice. Every driver is assumed to have a maximum patience in terms of extra time spent in traffic. This value is obviously differs for familiar and unfamiliar drivers.
- Trust: It should be clear that each user has varying trust on the VMS advise due to past experiences. This value is randomly generated for each vehicle.
- Cost: The perception of cost definitely affects the driver's decision of following the VMS advice. It is assumed that drivers who perceive a higher cost to delay are more tempted to accept VMS information. An average value of time is randomly assigned for each vehicle generated in the simulation.
- Familiarity: $T_{\min}$ for familiar and unfamiliar drivers are different. Thence, familiar

drivers are more prone to follow VMS information.

Programming in PARAMICS

PARAMICS Programmer is a framework that allows users to customize many features of the underlying simulation model. The customization is achieved through the use of API. The customization procedure includes:

- Passing additional network-wide configuration parameters into the simulation.
- Increasing the complexity of the routing and assignment algorithms
- The tuning of drivers and vehicle models and parameters (aggressiveness, perturbation, lane changing, etc.)
- Increasing the detail of the measured data available from simulation by vehicle tagging and using these tags trace the progress of the simulation (38).

API enables users to change the functions used in the simulation process and create new functions for specific purposes. Functions that can be changed or defined by the user are those, which act as “hooks” into the main simulation allowing the user to add additional routines via API. These functions are defined in a “plug-in” file, which creates dynamic link library files linked to the main simulation program.

PARAMICS has three basic stages **start-up**, **simulate** and **finish**. Each stage has one of more API functions associated with it. In the case of VMS route guidance the general outline of the API can be given as follows:

Start-Up

api_setup()

api_coefficient_file()

These functions load the network, retract the necessary information about the network (links, zones, VMS signs, VMS routes, etc.) and prepare look-up tables for vehicles and so on. This stage is called once at the beginning of the simulation.

Simulate

net_action()

vehicle_action()

vehicle_link_action()

link_action()

routing_decision()

net_post_action()

Each of these functions works differently within the simulation loop. For example, *net_action*() is called every time step of the simulation and can be used to update necessary data; on the other hand, *link_action*() is called for every link at each time step of the simulation. Similarly, *vehicle_link_action*() is called for every vehicle at every link in the network at each time step. Moreover, these functions must appear in the simulation is a given order. They cannot be "hooked" to the simulation process randomly.

Finish

end_action()

Called at the end of the simulation, allowing the plug-in to output summary information.

The available plug-in coded by the PARAMICS team is modified and customized for the analyses of this study. The modifications here appear in the availability of multiple routes for multiple controllers, and of the application of the bang-bang control theory.

Before getting into the simulation results, a succinct explanation of the simulation process of the plug-in is provided below. The API flowchart of the VMS route guidance is shown in Figure 8. The major *Paramics* functions used are *vehicle_link_action*, *net_post_action* and *routing_decision*.

At the beginning of the simulation the *vehicle_link_action* module checks every vehicle at every link in the network at each time step of the simulation. For example, if the time step of the simulation is 1 sec, all the vehicles in the network are scanned by this function at each second till the end of the simulation. Basically, as a vehicle is released from a zone, its status is checked using *vehicle_link_action* module. First it confirms that the vehicle is not "flagged" (meaning that if the vehicle is already under VMS control). If not, the module skips that vehicle and targets another one. If the vehicle is not flagged, the module checks whether the vehicle is traveling on a decision-making link (where the VMS sign is located). If not, function again skips that vehicle. If the vehicle is traveling on the decision-making link, then calling the user-defined VMS decision function in the plug-in file, it checks whether the vehicle accepts the VMS control or not.

At this point, a brief explanation of the *VMS decision* function will be given, since it appears as the key element in the API plug-in file. This function integrates all the driver behavior factors discussed in the previous section. For each vehicle that has not yet accepted VMS control and currently travels on a decision-making link, this function assigns numerical values for drivers' characteristics such as aggressiveness, awareness, patience, trust, etc using the available PARAMICS functions. After receiving a summation of the assigned values for each of these factors, each vehicle gets a "score." If the score is above a predetermined value, the vehicle "accepts" the VMS control and it is "flagged." If not, the vehicle follows its default route to its destination.

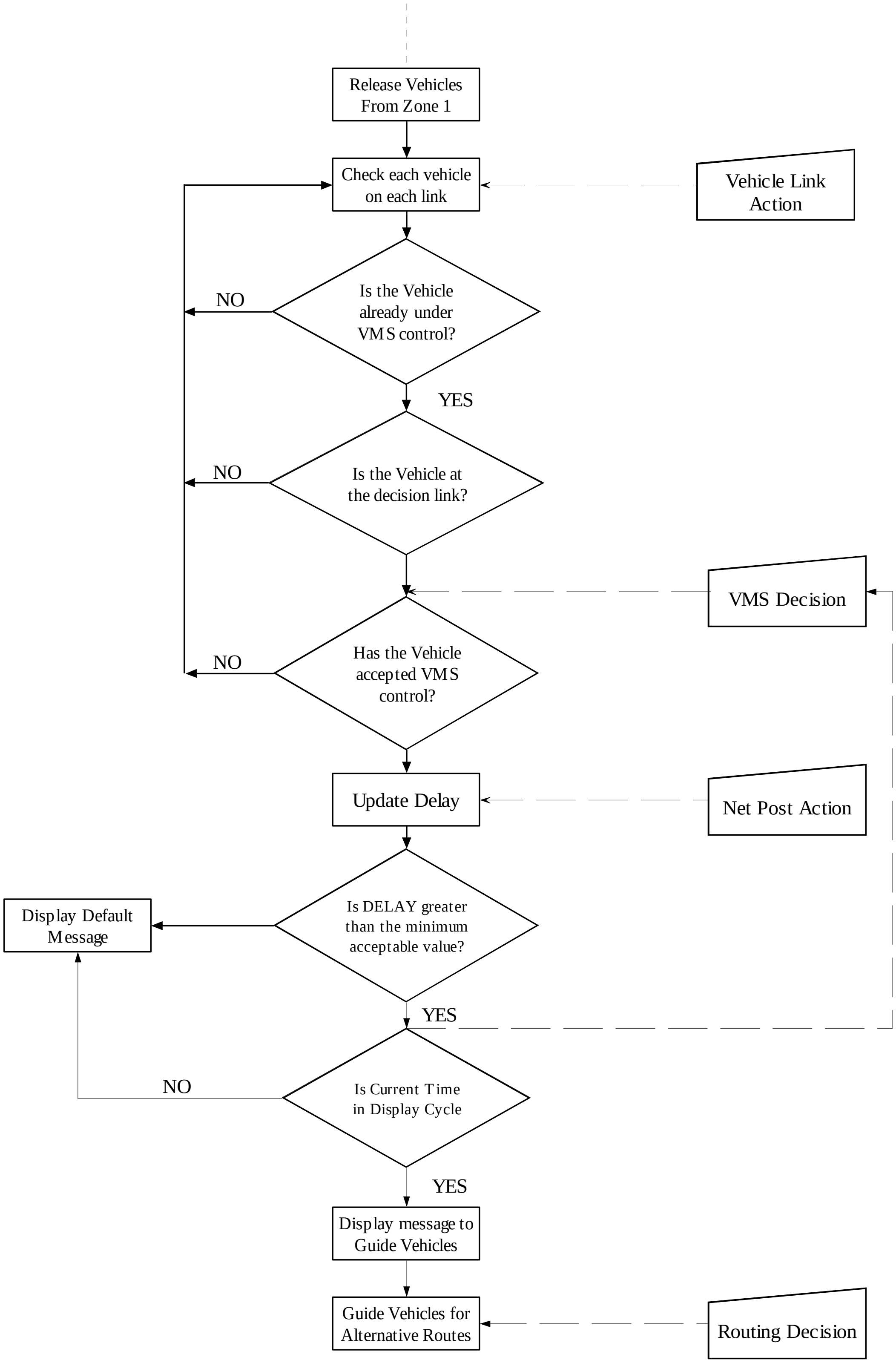


Figure 8. API process of VMS route guidance simulation

After the *vehicle_link_action*, the simulation moves forward to the next module. *Net_post_action* is called at each time step during the simulation after *vehicle_link_action*. It updates the delay measured on the “delay links” at each time step. In reality, the information update is executed with a certain delay. Hence to better characterize the real-life applications in simulation, the user can increase the time step of *net_post_action*. If a time step of 60 secs is defined for this function, then it will be called at each 60 secs during the simulation loop. So updates will be performed with a delay of 60 secs. After it updates the delay on the delay links, it searches the route with the minimum travel time. When a vehicle accepts VMS guidance, its decision is based on the statistics on route travel time that is collected in the *last time step* of the *net_post_action* module. So, if it accepts the VMS guidance it is also assigned to the route with the minimum travel time. Until it reaches its destination, the assigned route number is kept in the vehicle look-up table.

Routing_decision module leads the vehicle through the suggested links of the assigned route using this route number. As soon as the vehicle reaches off guidance routes, all its records are deleted from the database, and it ends its journey to its destination along its predetermined route.

As mentioned above, in the model analyses, a delay of 60 sec is used for *net_post_action* module. Future work will include the study of the effects of various information update delay values on the effectiveness of VMS guidance.

Simulation Analysis

The analyses here test the impact of single and multiple VMS structures in the network model. As mentioned earlier, (39) is used to determine the suitable VMS locations in the study area. In this report, the screening of the candidate VMS network is based on the following criteria (39):

- Existing overhead sign clutter should be taken into account,
- Placement should be at key decision points,

- Purpose and use of proposed sign(s),
- Off-freeway VMS should be only be used for regional diversions

Some of the suggested locations in this report are disregarded since they lie outside the limits our modeled network. Four of the potential locations are selected for the simulation analyses. These locations and the available routes controlled by the candidate VMS are shown in Figure 9. VMS 1 bypasses the traffic on the main route via an arterial roadway. VMS 2 and 4 divert vehicles on other freeways into the next on-ramps. VMS 4 on the other hand diverts vehicles to another highway to Philadelphia.

Since real-time traffic advisories are mostly utilized in the case of traffic incidents, we generate an accident along the main route to ensure that drivers require real-time information to avoid congestion caused by the accident.[1]

The network is simulated for 3 hours with the afternoon peak-hour demand level.[2] The incident starts at the 70th minute and ends at 90th. Each scenario is tested with six different seeds to take into account the stochastic nature of the simulation. For different simulation runs, we obtain different route choices mainly due to various seed values used for vehicle release rates, behavior of vehicle types, and vehicle dynamics. The differences in these characteristics reflect the hourly and daily fluctuations in traffic flows. Our findings presented here are based on the averages of these multiple runs.

Another important contribution in our simulation analysis is that we fixed the route travel costs between all O-D pairs during the incident. In PARAMICS, when feedback period option is utilized during the simulation of an incident, the vehicles will be aware of the delays due to that incident and start diverting to other available routes. This clearly reduces the impact of the incident on traffic congestion. Therefore, we first simulated the network for a non-incident scenario and collected the route travel costs using the API. Then we fed these costs into the simulation while simulating the ITS applications

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[1] NJDOT accident database indicates that within the last 3 years almost 15% of all accidents along the main route occurred at the selected location

[2] It should be noted that although the network is simulated for the afternoon peak, the travel direction is the opposite

during an incident. As a result, when vehicles start their journeys they apprehend non-incident costs on their routes although there exists delays due to the incident. This approach is assumed to be a very realistic approach since drivers are usually uninformed about the existing road conditions on their routes before they start their journeys.

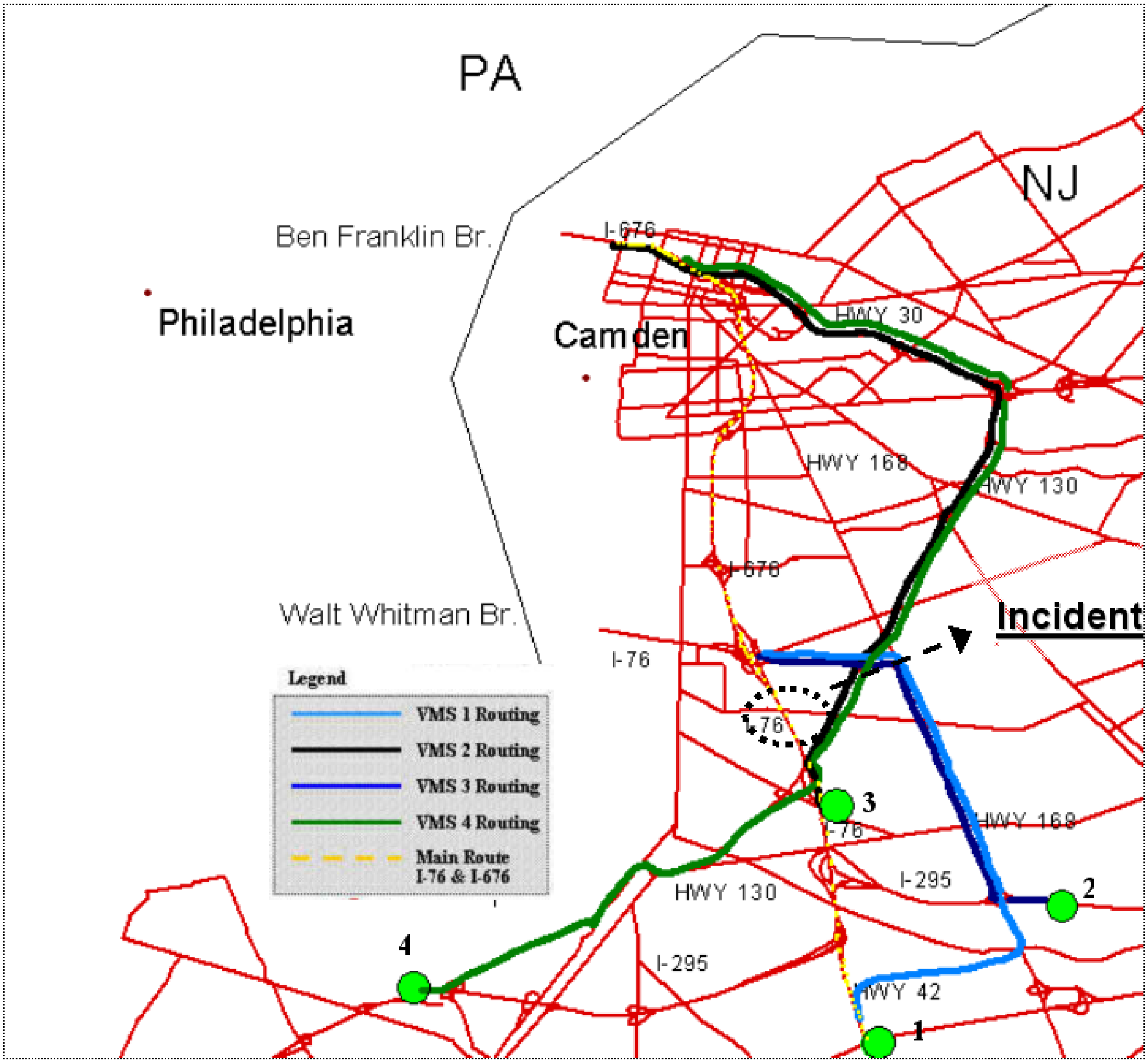

Figure 9.VMS locations and alternative routes

Discussions and Conclusions

One significant observation of the simulations is that, it is important to divert high numbers of vehicles; yet it is also important to decide how to and where to divert. That is to say, different types of diversions yield different impacts on traffic flow and travel times. It is observed that by-pass diversions, as in the VMS 1 scenario, can affect large number of vehicles; however, after they traverse the by-pass and merge on the main route, the mainstream traffic is highly disturbed due to higher weaving of vehicles. Similarly, rerouting of vehicles from the nearby highways to merge on the main route at another ramp, as in VMS 2, creates increased weavings during merging. This phenomenon significantly reduces the effectiveness of such VMS diversions, can be observed in Figure 10 and Figure 11.

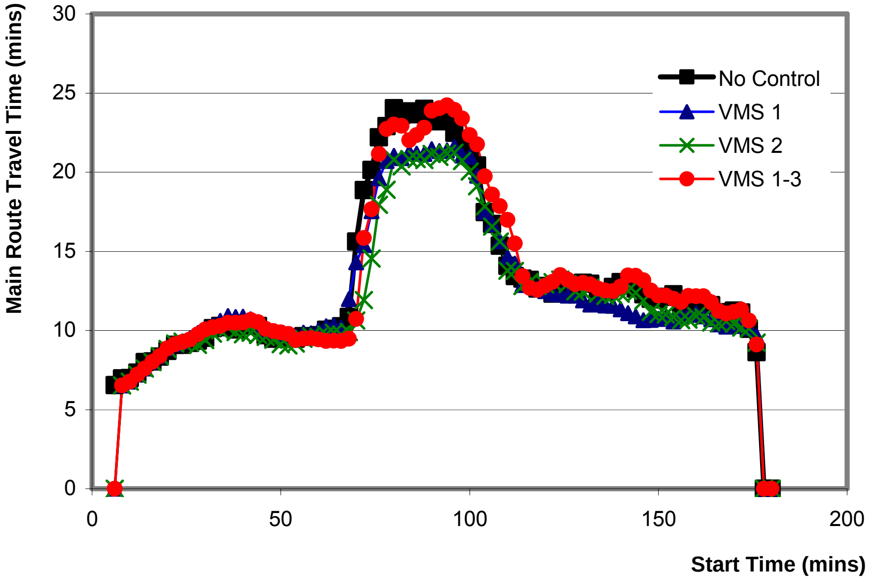

Figure 10. Comparison of main route travel times

As mentioned earlier, ITS technologies have network-wide effects beyond the highway section they are implemented. It is quite likely that when the traffic flow on a study corridor is regulated, other routes might be adversely affected. Especially, in VMS routing, traffic flow patterns along the alternative routes might be severely altered due to higher number of vehicles diverting. Therefore we present Table 3 to demonstrate average network travel times for each tested VMS scenarios. These values reflect the average travel time of all vehicles traveled in the network during the simulated period.

Based on these values, it can be stated that none of the scenarios seriously affect the travel times on other routes for the test network.

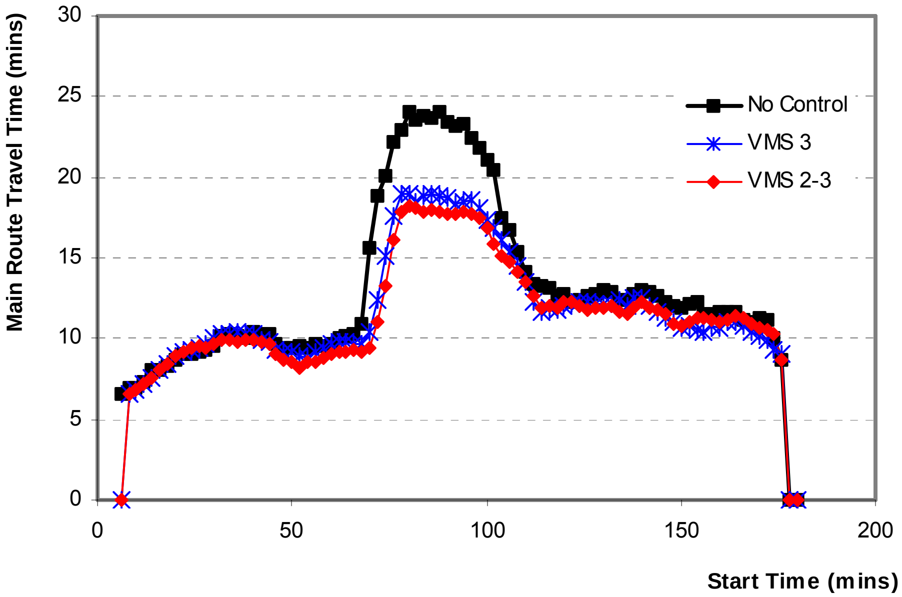

Figure 11. Comparison of main route travel times[3]

Table 3. Average network travel times

Scenarios	Average Travel Time (minutes)	Percentage Improvement (%)
No VMS	12.92	3.1
VMS 1	12.52	5.1
VMS 2	12.26	2.9
VMS 3	12.54	-1.2
VMS 4	13.07	-2.9
VMS 1&3	13.30	4.4
VMS 2&3	12.35	-0.31
VMS 3&4	12.96	3.1

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[3] Note that the impact of each VMS differs as they are incorporated with other VMSs. For example, though VMS 2 alone has little effect on route travel time, VMS 2-3 combination can yield a desirable effect. This is due to the fact that they both use the main route in the routing. As the number of vehicles diverted by each VMS alone changes as they operate together, the weaving phenomenon discussed in the text might disappear/appear. This explains why VMS 2-3 combination yields better results than VMS 2 and 3 separately.

The results presented here highly depend on the incident scenario. One way to consider the impact of various incident scenarios is to generate different incidents from the incident database for the study area. However, due to the very high computational costs, this will be a very time consuming process, especially considering the large number of scenarios simulated in this section. It is clear that such an extended analysis will provide mush better understanding of the impact of the simulated ITS strategy and need to be undertaken on a future project. Future work will focus on the evaluation using various incident scenarios.

RAMP METERING STRATEGIES

Introduction to Ramp Metering

In this section, we present three efficient ramp metering strategies that will be tested as part of the ITS scenarios identified in this report. Parsons Brinkerhoff report (39) suggested ramp metering as one of the major ITS technologies that can be deployed in NJ to improve traffic conditions. Ramp metering is a direct and efficient way to control and upgrade freeway traffic flow by regulating the number of vehicles entering the freeway. From previous theoretical investigations and field operational tests, it is well known that ramp metering has various positive effects such as (35):

- Maintain freeway operations at noncongested condition.
- Maximize mainline throughput.
- Increase travel speed (upstream and/or downstream, depending on the strategy).
- Reduce travel time.
- Reduce auto emissions and accidents due to a smoother mainline flow.

There are two major philosophies of ramp control strategies namely, local and system-wide. Local ramp control strategies consider an isolated section of the network consisting of a freeway section with one on-ramp, and respond only to the changes in the local conditions. On the other hand, system wide ramp metering is the application of metering to a series of entrance ramps with the goal of coordinating the response of all the ramps in the system. Another hybrid ramp metering strategy that combines local and system-wide ramp metering is known as hierarchical ramp metering. In this approach, a system-wide model at the upper level defines the overall desired network states, while a local model at the lower level performs to adjust the metering rate to achieve system states close to the system target.

Based on their responsiveness to the traffic, ramp control strategies can also be divided into two categories.

Pretimed Ramp Metering

Pretimed metering is the simplest form of on-ramp metering. Ramp metering rates are constant and determined based on off-line demand for particular time-of-day historical traffic observation data, without the use of real-time measurements of sensors. It can be effective in eliminating recurrent congestion, if severe incidents or sudden changes in demand that cannot be captured by the historical measurements do not occur. However, since traffic demand is not constant, it varies during day, and different days. Moreover, incidents may perturb traffic conditions in a non-predictable way. All these unexpected fluctuations in demand can render pre-timed ramp control strategies ineffective. These pre-time ramp control strategies may thus lead either to overload of the mainstream flow (congestion) or to underutilization of the freeway by achieving the opposite of it is trying to avoid, congested traffic conditions on the freeways (9).

Traffic Responsive Metering

In contrast, traffic responsive metering rates are determined based on information about the state of the traffic flow on the mainline and/or on the ramp traffic conditions. Based on the prevailing traffic conditions captured by real-time traffic data, such as occupancy, flow rate on the freeway and/or ramp, the metering rate are varied over time to effectively respond to traffic fluctuations. Ramp control systems can also be categorized as open loop and closed loop. In an open-loop ramp control system (demand capacity control, upstream occupancy control, etc.), the control input (for example, ramp metering rate) is independent of the system output, the existing traffic conditions (e.g., volume, occupancy, etc.). One of the important factors in freeway control is the management of the metering queue. In fact, a ramp metering application, aiming at avoiding or reducing congestion on the freeway, may have a positive or/and a negative impact on the adjacent road network traffic. In both demand-capacity control and upstream occupancy control, ramp-metering rate is set to minimum, if the threshold values for downstream capacity are reached or exceeded; therefore, on ramp queues are not handled directly in these ramp control strategies (15).

In this study, we will test three different ramp-metering strategies namely ALINEA, NEW CONTROL and MIXED CONTROL. The main reason for testing different ramp control strategies is due to the fact that the effectiveness of ramp metering is shown to increase based on the type on the control strategy used (48).

We will first give a detailed description of each ramp metering control strategy. Then, we will discuss the calibration of each control strategy using the simulated data obtained for the selected section of I-295 along which ramp metering strategies will be tested.

Description of Three Ramp Metering Laws (ALINEA, New Control and Mixed Control)

One can characterize freeway control to be open-loop (in general, time-of-day dependent) or closed-loop (traffic responsive). In the first case, control strategies are derived from a priori known traffic data, such as demands, origin-destination rates, etc., while traffic responsive control systems directly react to existing traffic conditions (36). There exists a large number of ramp metering schemes in literature. While some of them were implemented in the real world, most of these algorithms are still awaiting further assessment. In this section, the aim is not to review every ramp-metering algorithm proposed. Rather, the “feedback” based ramp-metering strategies, ALINEA (34), New Control and Mixed Control are introduced.

Alinea

A ramp-metering rate for an on-ramp is determined based on its local traffic conditions, such as flow, occupancy, travel speed, and occasionally queue over-flow on the metered ramp for the isolated ramp-metering algorithms. One of the algorithms in this category to be reviewed includes ALINEA (34), the first local ramp metering control strategy to be based on straightforward application of classical feedback control theory. ALINEA is a local-feedback control algorithm that adjusts the metering rate to keep the occupancy downstream of the on-ramp at a prespecified level, called the occupancy set point.

ALINEA uses feedback regulation to maintain a desired level of occupancy, or the target occupancy, which is usually chosen to be the critical occupancy, and apply the kinematic wave theory with locally calibrated fundamental diagrams as the underlying traffic model.

ALINEA, (See Figure 12) closed-loop ramp metering strategy, suggested by (34), to be applied at the time instants $kT, k = 0,1,2...,$ for any sample time interval T (e.g., $T = 60\sec$) is:

$$u(k) = u(k-1) + K_R[\hat{o} - o_{out}(k)] \tag{1}$$

Where $K_R > 0$ is a regulator parameter and $\hat{o}$ is a set (desired) value for the downstream occupancy (typically, but not necessarily, $\hat{o} = o_{cr}$ may be set, in which case the downstream freeway flow becomes close to q_{cap} , see Figure 13.

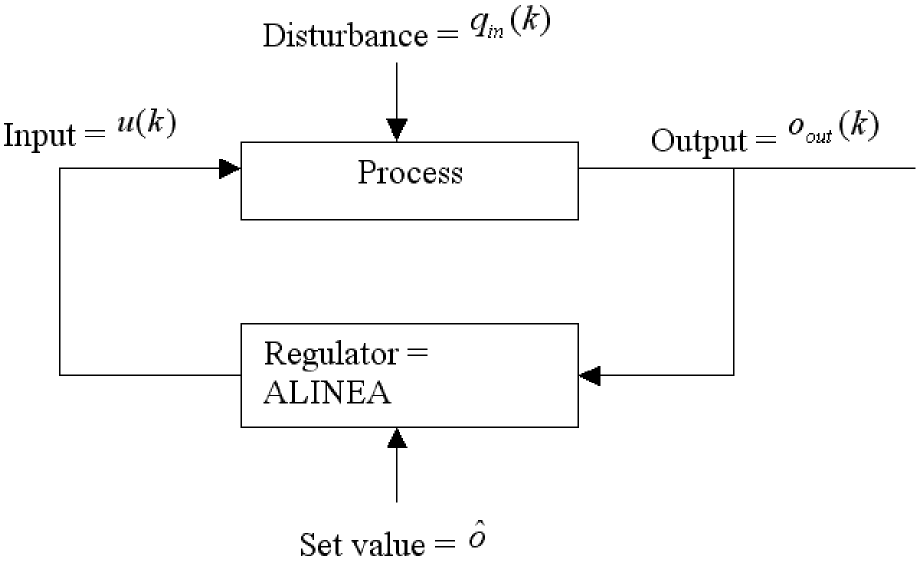


Figure 12.Block representation of the ALINEA algorithm (34)

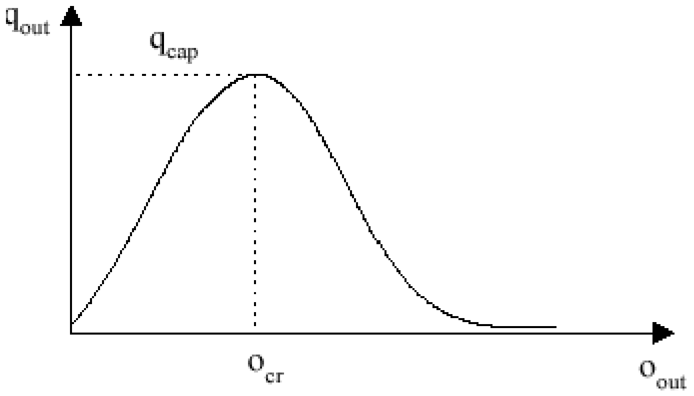


Figure 13. The fundamental diagram (26)

ALINEA can be described with the help of a block representation of the algorithm (See Figure 12). The process under control is the traffic flow on a freeway section with an on-ramp (See Figure 13). Traffic flow is affected by some process inputs. Process inputs that can be manipulated are called controllable inputs ($u(k)$, metered ramp on-ramp flow), whereas process inputs that cannot be manipulated are called disturbances

($q_{in}(k)$, freeway traffic inflow upstream of the ramp). Disturbances may be predictable or nonpredictable, measurable or nonmeasurable, and so on. In our case, $q_{in}(k)$ is the measurable disturbance, obtained with the help of detectors located on the freeway upstream of the on-ramp. The aim of this control is to appropriately select the controllable input ($u(k)$) so as to achieve-despite the impact of disturbances ($q_{in}(k)$)-a process output value ($o_{out}(k)$) that is close to desired level of occupancy on the freeway, called the "set value" ($\hat{o}$).

Equation (1) suggests a fairly plausible control behavior. If the measured occupancy $o(k)$ at time k is found to be lower (higher) than the desired occupancy, $\hat{o}$, the second term of the right-hand side of the equation becomes positive (negative) and the ordered on-ramp volume $u(k)$ is increased (decreased) compared to its last value of $u(k)$.

Clearly, the feedback law of the equation acts in the same way both for congested and for light traffic (no switching is necessary). ALINEA reacts smoothly even to slight differences $\hat{o} - o_{out}(k)$, and thus it may prevent congestion by stabilizing the traffic flow at a high throughput level. On the other hand, some demand-capacity strategies react to excessive downstream occupancies only after a threshold value is exceeded. Typically, and in contrast to ALINEA, the reaction of these control strategies to excessive occupancies is rather crude, i.e., on-ramp volumes are set equal to their minimal values. In this way, an unnecessary underload of the freeway may occur. On the contrary, the essential effect of ALINEA is to stabilize traffic flow at a high throughput level and eventually to reduce the risk of a breakdown without underloading the freeway.

The set value, $\hat{o}$, may be changed any time, and thus ALINEA may be embedded into a hierarchical control system with set values of the individual ramps being specified in real time by a superior coordination level or by an operator.

The regulator constant parameter K_R is the only parameter to be adjusted in the implementation phase because no thresholds or other constants are included in Equation (1). Furthermore, according to the theoretical considerations:

- The results of the control algorithm are insensitive for a wide range of K_R values,
- Increasing (decreasing) K_R values lead to stronger (smoother) reactions of the regulator, and regulation times get shorter (longer),
- For extremely high values of K_R, the regulator may have an oscillatory, unstable behavior.

In view of these statements, real life calibration of the unique free parameter K_R is particularly easy. Similarly, in the field implementation of ALINEA, only one detector station that measures occupancy $o_{out}(k)$, downstream of the merge area, is required. The measurement location should be such that a congestion originating from excessive on-ramp volumes is visible in the measurements.

A preliminary version of ALINEA and some popular previous control strategies have been implemented and tested on an on-ramp of the Boulevard Peripherique in Paris during an experimentation period of 6 months. Results of this study and other field results from current operational sites; such as, Brancion, Chatillion and Italie of the Boulevard Peripherique in Paris, showed a clear success of ALINEA in preventing congestion and increasing traffic throughput as compared to other local traffic-responsive strategies (34).

Advantages of ALINEA

- Simpler than other known algorithms,
- Requires a minimal amount of real time measurements (detectors),
- Easily adjustable to particular traffic conditions because only one parameter is to be adjusted in a prescribed way,
- Improved efficiency in preventing congestion and preserving capacity flow, compared to other known algorithms based on real life experiments,

- Can be embedded in a coordinated on-ramp control system,
- Can be modified easily in case of changing operational requirements,
- Highly robust with respect to inaccuracies and different kinds of disturbances, and
- Theoretically supported by automatic control theory.

For moderate congestion, ALINEA is effective, robust, and flexible. It is also easy to implement because the only parameters are the control gain and target occupancy.

The on-ramp values resulting from Equation (1) may be limited if some maximum or minimum values are exceeded. Moreover, override tactics (e.g., for preventing interference of the on-ramp queue with surface traffic) may be applied. When either a limitation or override tactic becomes active, green time for the ramp becomes the maximum value assigned.

Therefore, ALINEA does not consider on-ramp queue directly, which is generally handled through overriding restrictive metering rates, and would eventually have difficulty to balance freeway congestion and ramp queues when traffic becomes heavily congested.

New Control

New Control is a new nonlinear control design proposed by Kachroo and Ozbay (19) for an isolated ramp-metering problem is shown below:

$$u(k) = -K\left[o(k) - o_{cr}\right] + \left[q_{out}(k) - q_{in}(k)\right] \tag{2}$$

Where,

$u(k)$ is the metering rate at time step k

K is the regulator parameter (constant)

$o(k)$ is the current downstream occupancy at time step k

o_{cr} is the set occupancy value

$q_{in}(k)$ is the flow entering the freeway section at time step k

$q_{out}(k)$ is the flow leaving the freeway section at time step k

This control law guarantees that $\lim_{k\to\infty}(\rho-\rho_{cr})^2 \to 0$, which is the objective of the controller. In fact, it guarantees that the rate of convergence of $o-o_{cr}$ is geometric at a rate dictated by the control gain *K*. However, this control also does not take into account ramp queues. Instead, they are handled via threshold values depending on the storage capacity of the ramp.

Mixed Control

One of the major criticisms of the ramp metering has been the delay caused on the ramps due to the queues created by ramp control strategies that are developed to just optimize traffic flow on the freeway. Unacceptably long ramp queues can create spillover on the arterial streets by causing system-wide delays that mainly favor freeways. Moreover, the drivers who are stuck in long queues on the ramps that are metered can experience considerably high delays. Several States have been reluctant to deploy ramp-metering solutions due to these concerns about queue spillovers to the local streets.

It is true that most of the ramp control strategies proposed so far such as ALINEA and new section based control law (New Control) proposed in (17), shown in Equation (2), do not directly consider on-ramp queues. Instead, they are handled via threshold values depending on the storage capacity of the ramp.

Thus, the most popular implementation strategy that deals with ramp queues is to use override tactics that will turn off the ramp metering until the queue length is below certain threshold value. However, recently several researchers proposed strategies that explicitly take into account ramp queues while determining metering rates. For example, in a recent paper by (42), a modification to ALINEA control law shown in Equation (3) to control ramp-queue to avoid interference with surface traffic was proposed. A deadbeat controller that demands the queue length at the next time step to be equal to its set value $\hat{w}$ shown in Equation (3) was proposed:

$$r'(k) = -\frac{1}{T}[\hat{w} - w(k)] + d(k-1) \tag{3}$$

Where $r'(k)$ is the flow of vehicles entering the freeway, $\hat{w}$ is the set value chosen to be the maximum permissible queue length, $w(k)$ denotes the queue length at time-instant k, $d(k-1)$ is the demand flow entering the ramp. The proposed ramp metering rate $R(k)$ to be finally applied is given by

$$R(k) = \max\{r(k), r'(k)\} \tag{4}$$

Where $r(k)$ is the ramp-metering rate decided by ALINEA strategy (either original or the modified version).

Instead of using a rather rough logic for the queue threshold, a tighter ramp-queue control under the assumption that either a good estimate of the queue length or a measurement device such as a video sensor is available. With this modification, ramp-queue control is activated only when necessary and only to the extent necessary thus guaranteeing full utilization of the ramp storage space and a proper operation without oscillations.

Since aforementioned control laws use threshold activation approach to identify ramp queue formation these ramp-metering strategies are reactive rather than proactive. This type of reactive control, which depends on threshold activation, produces unwanted oscillations when it switches between trying to disperse the excessive ramp queue and trying to regulate mainline congestion. One possible way to avoid this problem is to adjust the metering rates in such a way that the overflow of ramp queues do not occur. The mixed ramp control law briefly described in this section attempts to achieve that objective by incorporating both freeway and ramp conditions into a single control law;

that is, mixed ramp control law explicitly considers ramp queues in its control law.

Mixed Control, the new “traffic responsive isolated ramp metering control law”, is developed to maximize the throughput on the freeway without creating long queues on the ramp. This goal can be achieved by developing a ramp metering control law that considers both queues on the ramp and traffic conditions on the freeway. This control algorithm shortens the long ramp queues, which are created by ramp metering, through the use of carefully calibrated weight parameters for freeway and ramp namely, (w_1, w_2).

Table 4. Descriptions of system variables

Variables	Description
$f_1(k)$	The flow entering the freeway section at time step k
$f_2(k)$	The flow entering the ramp at time step k
$u(k)$	Metered ramp flow at time step k
$\rho(k)$	Freeway density for section “i”
ρ_c	The critical value of section density (veh/mile)
$q_{out}(k)$	The flow leaving the freeway section at time step k
$queue_{ramp}(k)$	Queue length on the ramp at time step k
w_1, w_2	Weight factors, $w_1 + w_2 = 1$
K	Control gain, $0 < K < 1$
T	Time step duration
Δx	Length of the freeway section

The model of a freeway section is shown in Figure 14.

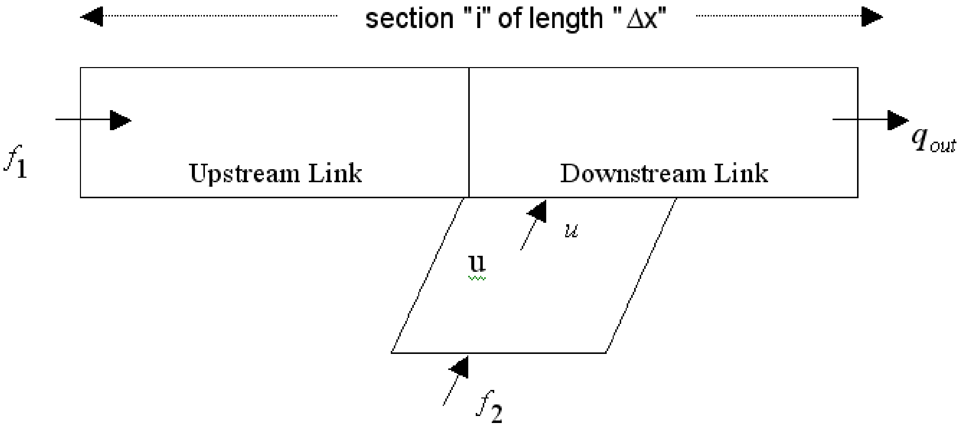


Figure 14. Isolated freeway ramp

Mixed Control can be described with the help of a block representation of the algorithm (Figure 15). The process under control is the traffic flow on a freeway section with an on-ramp (Figure 14).

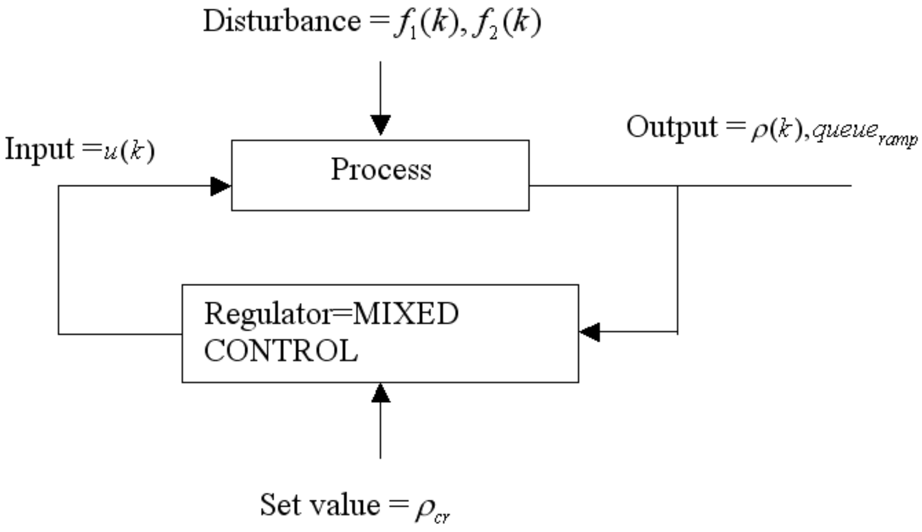


Figure 15. Block representation of the Mixed Control algorithm

The system shown in Figure 15 is affected by certain process inputs, which cannot be manipulated, called disturbances. This control system has two input measurement disturbances, f_1 and f_2, which are real time data from the detectors located on the freeway upstream (freeway demand) and on-ramp upstream (ramp demand), respectively. The states of the system are functions of disturbances, f_1 and f_2, respectively.

The objective of this feedback control design is to make the error variable go to zero. That is

$$\underset{t \to \infty}{Lt}\ e(t) = 0 \tag{5}$$

This traffic responsive ramp metering control achieves its goal, namely maximization of the throughput on the freeway without creating long queues on the ramp, by minimizing the following error function.

$$\text{Control Objective } e(k) = w_1 \mid \rho(k) - \rho_c \mid + w_2 queue_{ramp} \tag{6}$$

The error function, which takes into account these two objectives, determines how much importance should be given to freeway density and queue length on the ramp with the help of weights w_1 and w_2. Appropriate values of the parameters, w_1 and w_2, are determined by taking the objectives of the system into consideration. The system can be in two regions. One region is where the traffic density is greater than the critical density. The other region is where the traffic density is equal to or less than the critical density. Two sub-sections can be combined to come up with a unified control law that is applicable in both regions. The overall control law therefore is given by

$$u = G^{-1}[-F - Ke(k)] \tag{7}$$

Where

$$F = sign(\rho(k) - \rho_c)w_1[\rho(k) - \rho_c + \frac{T}{\Delta x}(-q_{out}(k) + f_1(k))] + w_2[queue_{ramp}(k) + Tf_2(k)] \tag{8}$$

And

$$G = [sign(\rho(k) - \rho_c)w_1 \frac{1}{\Delta x} - w_2]T \tag{9}$$

The complete derivation of the above control law that is outside the cope of this report is given in (19).

Advantages of Mixed Control

Mixed control has clear and simple algorithm compared to other known nonlinear algorithms. Mixed Control uses feedback regulation to achieve its objective, maximization of the throughput on the freeway without creating long queues on the ramp. This control law, theoretically supported by automatic control theory, is derived from the fundamental equation of conservation of traffic flow.

In the simulation of Mixed Control, three detectors, that measures freeway traffic flow upstream of the ramp (f_1), traffic volume demand on the ramp (f_2), freeway traffic flow downstream of the ramp (q_{out}) are required.

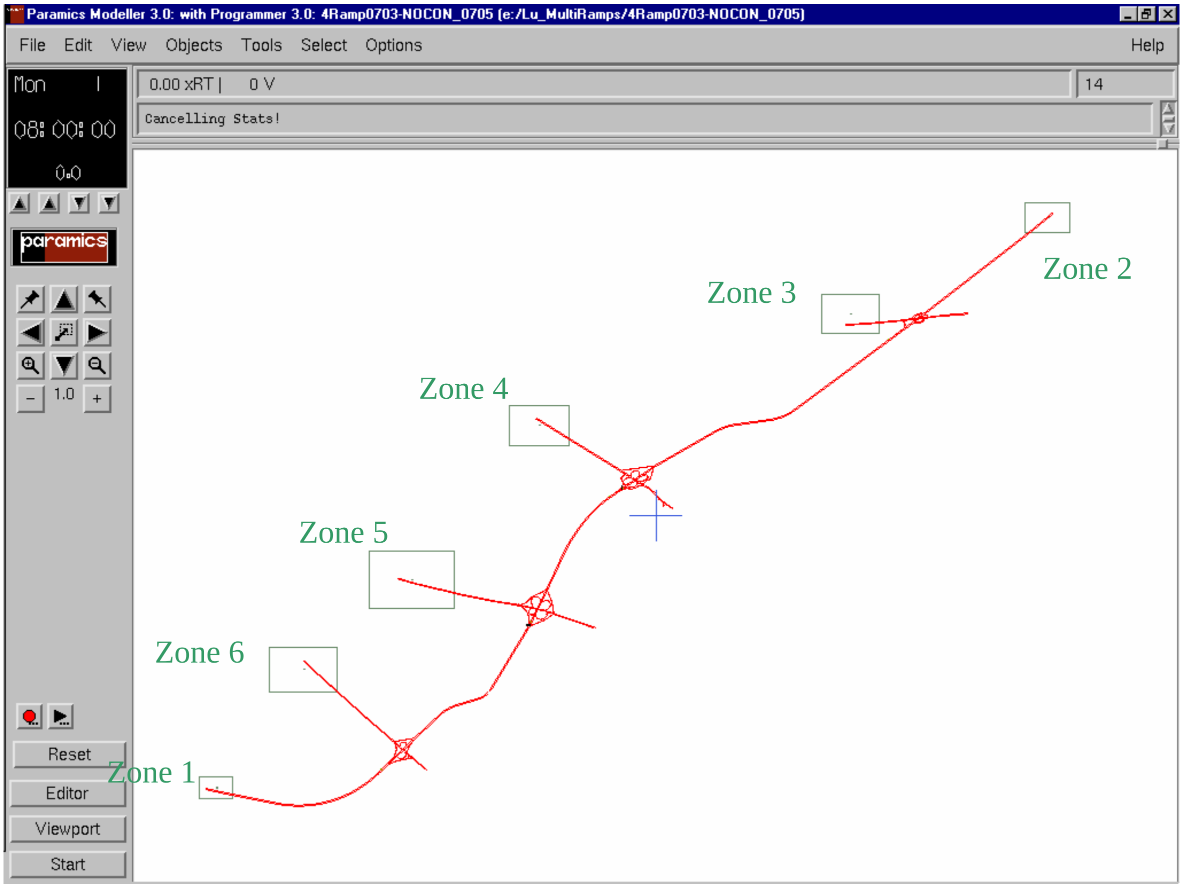
For moderate congestion, Mixed Control is effective, robust, and flexible. It is also easy to implement because the only parameters to be calibrated is the control gain. Critical density and weight factors, w_1 and w_2, can be changed any time in case of changing operational requirements, and thus Mixed Control may be embedded into a hierarchical control system with set values of the individual ramps being specified in real time by a superior coordination level or by an operator.

Contrary to ALINEA, because of its nonlinear nature, Mixed Control is effective both for regulating congested and noncongested traffic when the nonlinearities in traffic behavior present. On ramp queue is considered in Mixed Control by calibration of the weighting parameters for freeway and ramp, accordingly; therefore, no overriding tactics (e.g., for preventing interference of the on-ramp queue with the surface traffic), whereas ALINEA does not consider on-ramp queue directly, which is generally handled through overriding restrictive metering rates, and would have difficulty to balance freeway congestion and ramp queues when traffic becomes heavily congested.

PARAMICS Model Description of the Multi-Ramp Network

The freeway simulated in this study is Highway I-295 located at southern New Jersey. This highway section includes the junctions of I-295 with Route 38, State HWY 73, State HWY 70 and Berlin RD. This section of I-295 was selected proposed because it is a very appropriate test site for evaluating the effectiveness of ramp metering in the SJ network as proposed by (39). In this study, only the southbound traffic was simulated.

Figure 16 shows a screen capture of the PARAMICS model of the freeway and ramps created using the available geometric data. There are 4 intersections, all of which are selected for the ramp metering implementation in this study. Length of the corridor from Zone 2 to Zone 1 is 11.0 mile. Speed limit on the freeway links is 60mph. Six O-D demand zones were created in the network as shown in Figure 16. The traffic demand matrix used in PARAMICS model is shown in Table 5.



Paramics Modeller 3.0: with Programmer 3.0: 4Ramp0703-NOCON_0705 (e:/Lu_MultiRamps/4Ramp0703-NOCON_0705)

Cancelling Stats!

Figure 16. The network with 4 on-Ramps and 4 off-ramps

Table 5. Demand matrix for the multi-ramp network[4]

	To zone 1	To zone 2	To zone 3	To zone 4	To zone 5	To zone 6	Total
From zone 1	0	0	0	0	0	0	0
From zone 2	4450	0	0	5	0	0	4455
From zone 3	0	0	0	520	0	0	520
From zone 4	0	0	0	0	520	0	520
From zone 5	520	0	0	0	0	0	520
From zone 6	520	0	0	0	0	0	520
Total	5490	0	0	525	520	0	6365

The geometric information of the major detectors is given in Table 6.

Table 6. Geometric information of major detectors

DETECTORS	FREEWAY LINE	CROSSING STREET	NO. OF LANES		UD (FT)	DD (FT)
			Mainline	Ramp		
F11-F12	I-295 SB	Route 38	3	1	752.4	365.6
F21-F22	I-295 SB	State HWY 73	3	1	790.9	537.3
F31-F32	I-295 SB	State HWY 70	3	1	868	396.2
F41-F42	I-295 SB	Berlin RD	3	1	797.8	531.9

UD is the distance from the upstream detector and the ramp nose. DD is the distance from the downstream detector and the ramp nose. There are also two detectors located on each on-ramp. One of the two detectors on the ramp is located downstream of the on-ramp, and another is at the upstream. These two detectors are used to collect the queue length at the ramp and also the release rate of the ramp.

The vehicles file, which was generated automatically, was edited to represent the traffic on the study network (type 14 cars) (37). The characteristics of each vehicle, and assignment information for each vehicle type were specified in this file.

Two files namely, the configuration file and the measurements file to extract PARAMICS model statistics were edited. The configuration file is generated automatically, whereas

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[4] 0 demand in the table is due to the fact that only south bound traffic is simulated in the study.

the measurements file has to be created in order to specify the data requirements to be gathered. In the measurements file, “gather link data” was written to be able to collect link flow, link speed, and link density, and “gather trip info” was coded to obtain the travel times for the links of the specified trips from zone to zone. Trip information requires a separate file, called trips file, which is used to specify the trips for travel time data collection.

In order to better evaluate the effectiveness of each ramp metering strategy the simulation was run for the I-295 corridor that is isolated from the rest of the network. This was done to isolate the network-wide effects and to mainly focus on the freeway control. In this section, the same ramp control algorithms will be run in the context of the overall test network and for all scenarios network wide impacts will then be evaluated. The simulation was run for 3 hours and 15 minutes, allowing the initial 1 hour 15 minutes for loading the facility and 1 hour at the end to eliminate any effects from the simulation ending. The values of the parameters used in PARAMICS model are specified in “configuration” file. Using configuration and measurements files, statistics were collected for the one-hour portion of the simulation from the detectors.

The simulation was run with three different seeds (150, 250, 1000) for each scenario, and the average of the results are tabulated in the simulation results section.

Calibration of Ramp Metering Parameters

In PARAMICS plans file, the control law equation for each ramp metering control was converted into green phase time using:

$$g = (u / u_{sat}).C \tag{10}$$

where C is the cycle length (sec), u is the ramp metering rate (veh/cycle), $u_{saturated}$ (veh/cycle) is the saturated ramp flow. Therefore, the unit of each gain parameter is different from the unit definition in the original control laws of ALINEA, New Control and Mixed Control shown in equations. After implementing ALINEA, New Control and Mixed Control using plans and phases files within PARAMICS Modeller, a series of simulation runs were carried out to determine the gain parameter, K, as it is complicated to analytically determine K value that produces desirable performance for each ramp metering control law.

This approach is similar to the one adopted by Zhang et al. (48). Similarly, the weight ratios (w_1 and w_2) used in mixed control implementation are determined from a series of simulation runs.

Implementation of the ramp metering algorithms to be evaluated requires the knowledge of critical occupancy at downstream of each ramp metered. In PARAMICS, critical occupancy can be attained by means of occupancy-flow plots for given detectors. According to these plots for each lane on the downstream of the on-ramp (Figure 17 and Figure 18), it is found that critical occupancies for the ramp1, ramp2, ramp3 and ramp4 are 25%, 25%, 25% and 26%, respectively. However, for the ramp metering implementation purposes, set occupancies for ramp1, ramp2, ramp3 and ramp4 are selected as 24%, 24%, 23%, and 24%, respectively.

Time step was taken as 2, the default time step, which provides that calculation are done every 0.5 seconds of simulation.

After the model calibration, the output is observed to represent field data within an acceptable level of accuracy. Therefore, the calibrated and validated model for the selected section of I-295 is used to simulate the traffic operations of the study site.

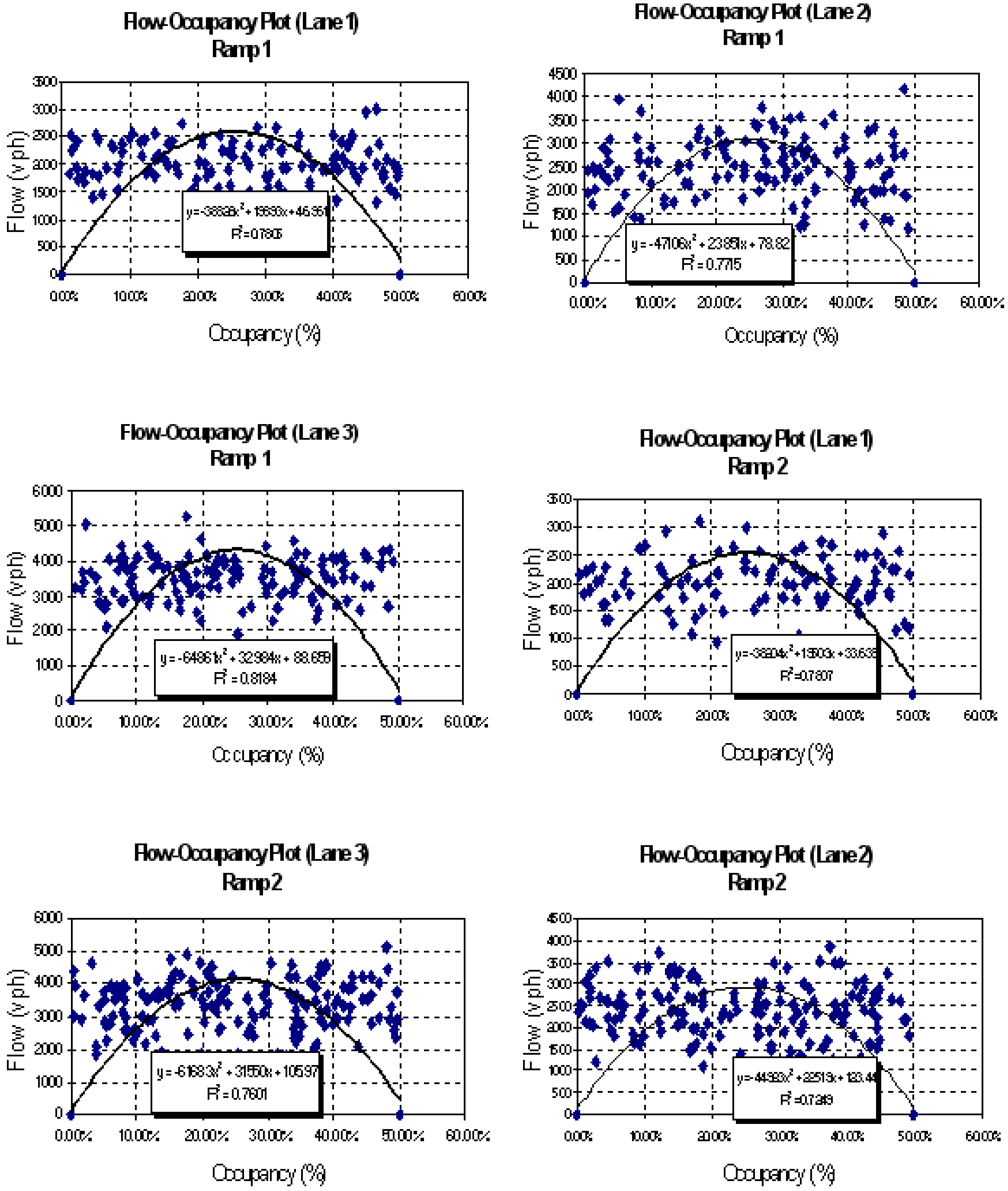


Figure 17. Flow-occupancy pots (lane 1-5 of each ramp) for the section of I-295

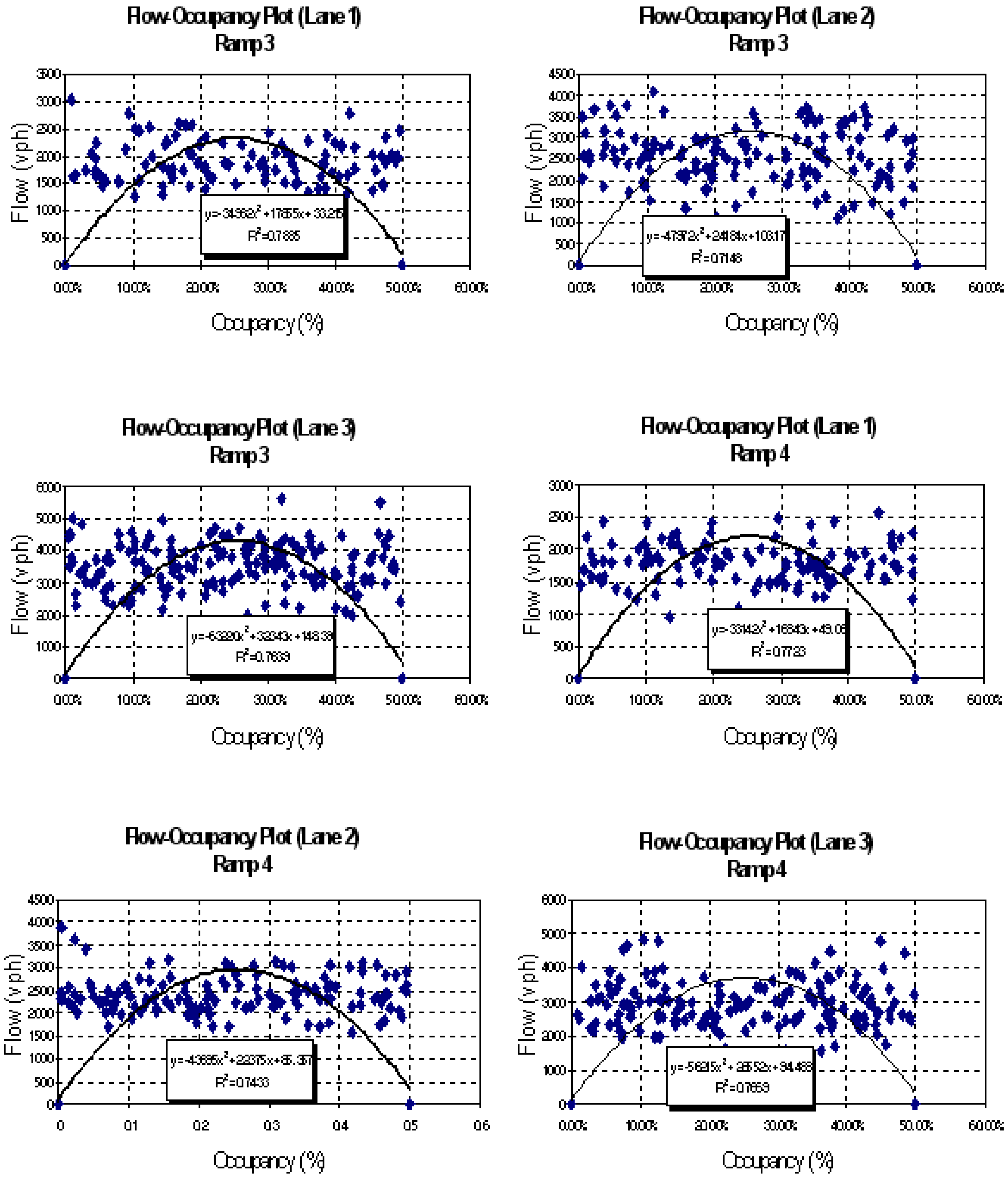


Figure 18. Flow-occupancy pots (lane 1-5 for each ramp) for the section of I-295

Measures of Effectiveness Used

Once the simulation model is developed, calibrated and finally validated, it is important to determine how the selected ITS technologies will be evaluated. The measures of effectiveness used are given in the following.

One of the measures of effectiveness used in the ramp metering evaluation is the mean congestion duration (sec) on the downstream freeway link. Mean congestion duration is the accumulated period of time during the simulation where the measured occupancy per time interval (20 sec) is larger than the critical occupancy, $o_{cr} = 26\%$.

$$Mean\,CongestionDuration\,(\text{sec}) = n.T \tag{11}$$

Where n is the number of times the measured occupancy on the downstream link is larger than critical occupancy, T is the time step interval (20 sec).

Occupancy of the freeway section (both upstream and downstream of the ramp) is gathered by means of plans file report for each time step (20 sec). The following formula gives one-link's (upstream or downstream) mean occupancy based on the occupancy measurements in n time steps:

$$Mean\,Occupancy(\%) = \frac{\sum_{i=1}^{m} o_i}{m} \tag{12}$$

Where o_i is the occupancy on the downstream freeway link at time step i, m is the number of time step during the simulation

Another measures of effectiveness for the evaluation of the ramp controls is average speed, density and flow on the freeway and ramp links. Speed (mph), flow (veh/hour) and density (veh/mile) measurements for each time step on each link in the study section were gathered from the PARAMICS output statistics every minute during the simulation. Then, using following formula, the averages for each measures are obtained for each link in the system (one upstream link, one downstream link and one ramp link).

$$Mean\ Speed\ (mph) = \frac{\sum_{i=1}^{m} S_i}{m}, Mean\ Density\ (veh/mile) = \frac{\sum_{i=1}^{m} D_i}{m},$$
$$Mean\ Flow\ (veh/hour) = \frac{\sum_{i=1}^{m} F_i}{m} \quad (13)$$

Where S_i is the speed on one link at time step i, D_i is the density on the link at time step i, F_i is the instantaneous flow at time step i, m is the number of time step during the simulation.

Another performance measure used to analyze the impact of ramp metering is to compare the travel times for the upstream downstream sections and ramp links, which are calculated using the following equation:

$$Average\ Link\ Delay\ (veh.hour) = (ATT \times p)/3600 \quad (14)$$

Where ATT (sec) is the average travel time spent on the link (downstream, upstream, or ramp link) per vehicle , which is obtained in the specific PARAMICS output file named "trips link delay", p (veh) is the total number of vehicles on the link during the simulation period.

On-ramp queue length is the number of vehicles on the ramp per time step (20 sec). This measure is gathered through PARAMICS plans report data for each time step. Then, the average length of the on-ramp queue (on one-ramp-link) per time interval (20 sec) was found using following equation:

$$On - ramp\ queue\ (mph) = \frac{\sum_{i=1}^{m} queue_{ramp\,i}}{m}, \quad (15)$$

Where $queue_{ramp\,i}$ is the on-ramp queue at time step i, m is the number of time step during the simulation.

Testing the Ramp Metering Strategies

Description of Scenarios for the SJ Network

In this section, ALINEA (34), New Control (19) and Mixed Control are implemented on the Multi-ramp network, where all 4-on-ramps are metered. First, the simulation model of the study network is described. The performance of three ramp metering strategies are then compared using the measures of effectiveness explained in the previous chapter, with respect to each other as well as with respect to the “No Control” case.

Implementation of the Control Strategies

The time interval to update the metering for all controls is equal to 17 seconds and the weighted average of the occupancies on the mainline, are summed over that interval by means of a counter. Then, the weighted averages of all the lanes’ (on the mainline) occupancies are obtained for that interval. It is also ascertained that the calculated occupancies do not exceed the maximum value allowed for the occupancy (100%) due to mainly internal numerical errors committed by PARAMICS while collecting link statistics. The cycle length of the signal for the ramp is considered as fixed. If the initial calculated value of green time is less than 2 seconds or greater than 15 seconds, the algorithm forces the value to be within this range (Since the time step chosen in simulation is taken as 2, the calculation are conducted every 0.5 seconds of the simulation).

Next, each evaluation scenario is briefly described.

No Control Scenario Implementation

No ramp metering strategy is used in the simulation for this scenario, which is the base scenario for comparative analysis with the control implementations. Under this condition, vehicles entering the mainline stream from ramps will not be regulated, and the only restriction is the inherent gap acceptance of each vehicle.

ALINEA Implementation

In order to avoid interference with surface street traffic, a queue override strategy that sets the green time to its maximum allowed value when the occupancy of the ramp detector exceeds a certain threshold is integrated into the ALINEA algorithm. The maximum numbers of on-ramp vehicles allowed on ramps 1, 2, 3 and 4 are 21, 29, 39 and 18, respectively.

New Control Implementation

In New Control implementation, since the queue on the ramp is not taken into consideration in the control law, the similar threshold as in ALINEA strategy was used for the on-ramp queue. The maximum numbers of on-ramp vehicles allowed on ramps 1, 2, 3 and 4 are 7, 16, 27 and 10, respectively.

Mixed Control Implementation

In Mixed Control implementation, control gain, K, and weight factors w_1 and w_2 were calibrated as 0.7, 0.175 and 0.825 (for all the ramps), respectively. Unlike ALINEA and New Control, Mixed Control performs satisfactorily without a queue override strategy that shuts off the ramp metering and creates unwanted fluctuations. This way of regulating smoothly the freeway and queue build-ups makes it more desirable to other control strategies that do not explicitly consider the queues specifically created as a result of ramp metering.

Simulation Results for Recurrent Congestion for All Control Laws

All four scenarios (No Control, ALINEA, New Control and Mixed Control) were run three times each with different seed values (150, 250, 1000). This is because the random number seed in PARAMICS sets the random number generator starting point, and varying this value guarantees a different outcome from the simulation each time due to random release of traffic by the program and the effect of seed number on driver behavior models such as car following, lane changing and gap acceptance. Thus, in this section, the average of three seeds is tabulated as the result of the multi-ramp network simulation. The measures of effectiveness used to evaluate the control strategies based on the PARAMICS model are described in Measures of Effectiveness Used section.

Simulation results demonstrated in Table 7 and Table 8 show that all the control strategies were able to reduce the average upstream and downstream occupancy compared to No Control scenario. From these tables it can be observed that all controllers successfully reduced the average occupancies to close or below the critical occupancies; therefore, the controllers were able to keep the traffic on the freeway moving more smoothly.

It should be noticed that among the four intersections, the controllers performed better at some of the intersections, and at other intersections the improvement can be limited. This can be explained as follows: ALINEA, New Control and Mixed Control are all local feedback ramp-metering strategies. When metering is implemented on one specific ramp using these controls, the traffic conditions on the other ramps are not considered for determining the ramp metering rates at this ramp. Therefore, it is inevitable that all the controls are not able to provide improvements for all the ramps. In the No Control case, however, first three intersections has fairly congested conditions compared to the last intersection, which led to less vehicles to be released towards the fourth intersection. Therefore, intersection four has low upstream and downstream occupancy, speed, density and flow. This also explains why the improvement achieved by the controller is insignificant on the last two ramps compared to improvements on the ramp1 and ramp2.

Except the third ramp, Mixed Control provided the largest reduction in the downstream occupancies of each intersection. Similarly, except the last ramp, ALINEA and New Control were also successful in reducing the downstream occupancies for all the intersections. This was due to the fact that with the control implementations, congestion was relieved in the first two intersections. However, more vehicles are released from the first two ramps toward the last two ramps. This leads to deterioration in those last ramps.

Table 7. Average upstream and downstream occupancies for ramps

	Up1	%change	Down1	%change	Up2	%change	Down2	%change
No Con	24.70%		25.63%		20.16%		29.21%	
Alinea	20.94%	-15.24%	22.03%	-14.03%	15.92%	-21.03%	25.85%	-11.50%
New Con	20.51%	-16.97%	21.58%	-15.79%	14.80%	-26.59%	26.17%	-10.40%
Mixed Con	20.40%	-17.42%	21.49%	-16.14%	16.82%	-16.59%	25.81%	-11.63%

Table 8. Average upstream and downstream occupancies for ramps

	Up3	%change	Down3	%change	Up4	%change	Down4	%change
No Con	28.47%		30.27%		29.16%		27.48%	
Alinea	23.85%	-16.22%	24.72%	-18.32%	29.37%	0.72%	27.99%	1.85%
New Con	26.23%	-7.87%	27.50%	-9.16%	28.85%	-1.04%	28.19%	2.61%
Mixed Con	25.62%	-10.00%	26.93%	-11.04%	27.83%	-4.57%	27.18%	-1.09%

Table 9 and Table 10 show the maximum value of occupancy collected at the upstream and downstream of the freeway. It can be observed from these tables that both controllers made some improvement with respect to the occupancies at upstream and downstream of the intersections compared to No Control scenario. However, except the Mixed Control scenario, all the controls resulted in increase in maximum downstream occupancy at the fourth ramp.

Table 9. Maximum upstream and downstream occupancies for ramps

	Up1	%change	Down1	%change	Up2	%change	Down2	%change
No Con	61.94%		62.92%		72.95%		69.18%	
Alinea	37.86%	-38.88%	35.52%	-43.54%	58.12%	-20.32%	57.03%	-17.56%
New Con	35.82%	-42.17%	35.79%	-43.11%	55.39%	-24.06%	63.71%	-7.91%
Mixed Con	36.21%	-41.54%	34.80%	-44.69%	67.09%	-8.02%	62.67%	-9.41%

Table 10. Maximum upstream and downstream occupancies for ramps

	Up3	%change	Down3	%change	Up4	%change	Down4	%change
No Con	80.53%		71.72%		71.84%		45.36%	
Alinea	68.19%	-15.32%	61.23%	-14.62%	64.44%	-10.30%	52.84%	16.50%
New Con	73.90%	-8.23%	68.71%	-4.20%	63.70%	-11.32%	49.21%	8.48%
Mixed Con	72.84%	-9.56%	66.39%	-7.44%	62.17%	-13.46%	43.49%	-4.13%

The mean congestion duration shown in Table 11 is the accumulated period of time during the simulation, where the measured occupancy is higher than the critical occupancy for each downstream of the intersection. It can be seen that, for the overall of 4 intersections, all the controls made significant improvements for relieving the congestion.

Table 11. Mean congestion duration on the downstream freeway link for each ramp

	Ramp 1	%change	Ramp 2	%change	Ramp 3	%change	Ramp 4	%change	Total	%change
No Con	27.89	-	37.67	-	39.67	-	33.33	-	138.56	-
Alinea	19.11	-31.48%	31.67	-15.93%	26.56	-33.05%	36.22	8.67%	113.56	-18.04%
New Con	18.11	-35.07%	33	-12.40%	32.11	-19.06%	35	5.01%	118.22	-14.68%
Mixed Con	15.56	-44.21%	31.56	-16.22%	33.11	-16.54%	34.22	2.67%	114.45	-17.40%

The improvement in mainline upstream and downstream flows as a result of the implementation of the control strategies was insignificant as it can be seen in Table 11.

Table 12. Total traffic volumes on the freeway at each intersection (total of 3 lanes)

Intersection No	Location	No Con	Alinea	New	Mixed
1	upstream	4375.45	4335.45	4394.73	4352.21
	%change		-0.91%	0.44%	-0.53%
	downstream	4969.51	4955.01	4898.56	4875.96
	%change		-0.29%	-1.43%	-1.88%
2	upstream	4317.4	4274.22	4269.31	4283.13
	%change		-1.00%	-1.11%	-0.79%
	downstream	4858.04	4862.42	4818.32	4783.38
	%change		0.09%	-0.82%	-1.54%
3	upstream	4434.67	4478.15	4291.23	4405.73
	%change		0.98%	-3.23%	-0.65%
	downstream	4903.4	4791.69	4851.7	4769.52
	%change		-2.28%	-1.05%	-2.73%
4	upstream	5015.99	4902.13	4952.62	4885.89
	%change		-2.27%	-1.26%	-2.59%
	downstream	5354.86	5199.05	5336.13	5216.2
	%change		-2.91%	-0.35%	-2.59%
Average of 4 Intersections		4778.67	4724.77	4726.58	4696.50
%change		-	-1.13%	-1.09%	-1.72%

The mean speed on the freeway at each intersection is given in Table 13 and the time-dependent speed values on the upstream and downstream of the freeway at each intersection are given in Figure 19 and Figure 20. For intersection 1, 2 and 3, the controllers made noticeable increase to the mean speed. However, for intersection 4, for the same reason explained above, the controllers did not produce considerable level of benefit.

Table 13. Mean speed on the freeway at each intersection (avg. of 3 lanes)

Intersection No	Location	No Con	Alinea	New	Mixed
1	Upstream	48.82	51.56	50.63	52.45
	%change		5.62%	3.71%	7.44%
	Downstream	52	60.94	61.06	60.26
	%change		17.18%	17.41%	15.88%
2	Upstream	51.15	57.17	58.71	55.53
	%change		11.76%	14.78%	8.56%
	Downstream	46.03	52.92	51.81	52.06
	%change		14.95%	12.56%	13.08%
3	Upstream	48.05	57.54	52.69	53.62
	%change		19.75%	9.65%	11.59%
	Downstream	43.65	53.8	48.26	48.26
	%change		23.25%	10.56%	10.56%
4	Upstream	47.96	47.43	47.69	48.63
	%change		-1.11%	-0.55%	1.41%
	Downstream	49.69	48.64	48.97	51.05
	%change		-2.12%	-1.45%	2.73%
Average of 4 Intersections		48.42	53.75	52.48	52.73
%change		-	11.01%	8.38%	8.91%

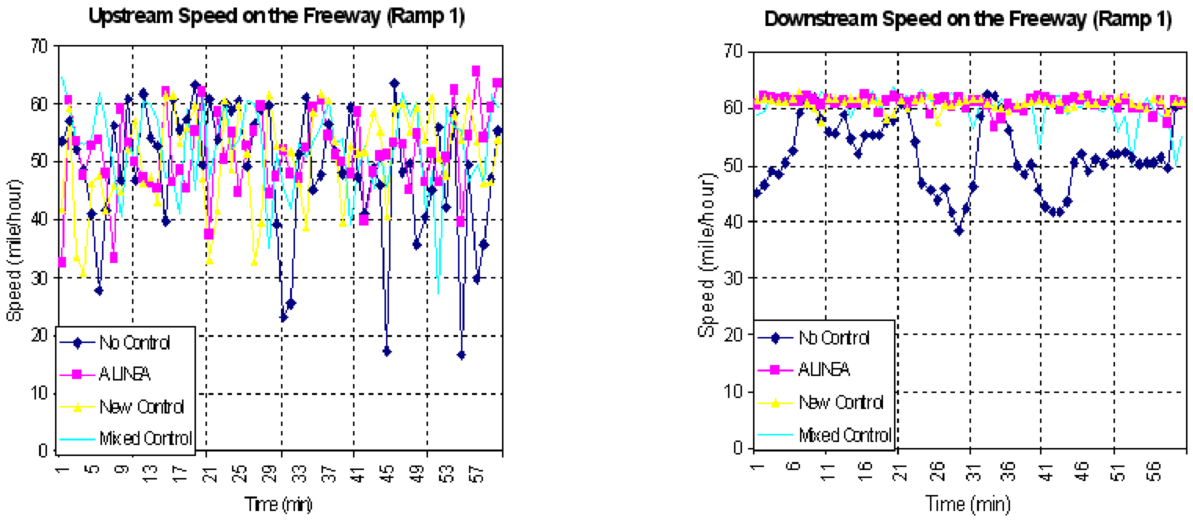


Figure 19. Average time-dependent speed for 3 lanes on upstream and downstream section of ramp 1

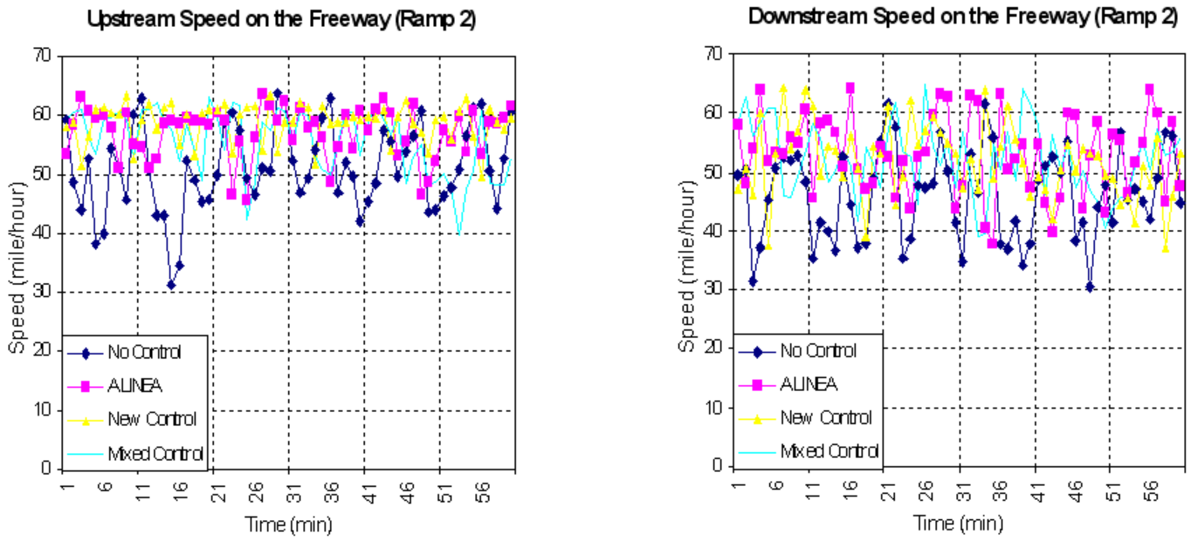


Figure 20. Average time-dependent speed for 3 lanes on upstream and downstream section of ramp 2

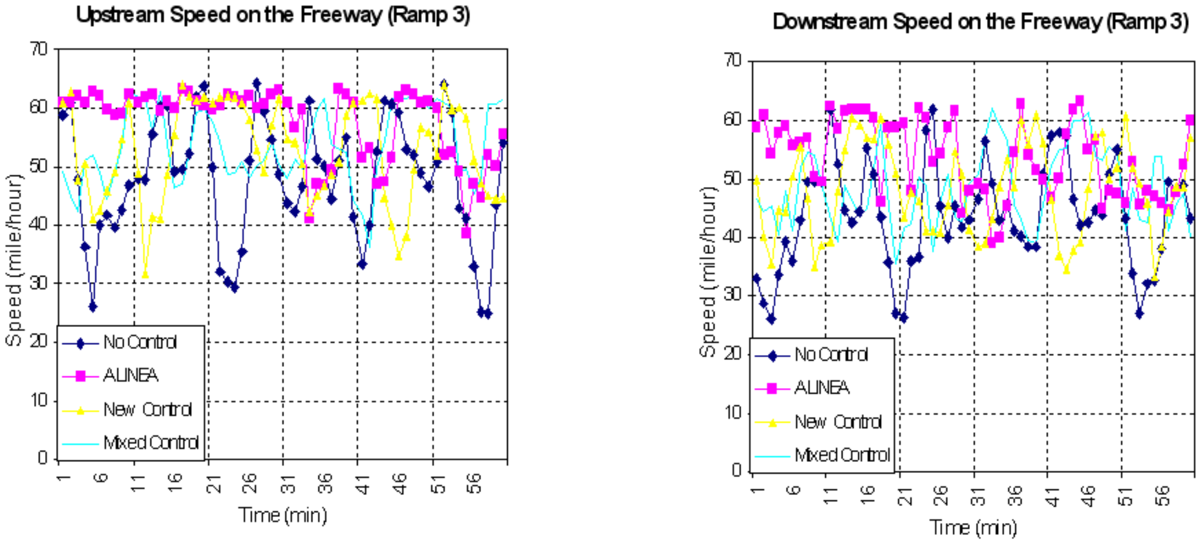


Figure 21. Average time-dependent speed for 3 lanes on upstream and downstream section of ramp 3

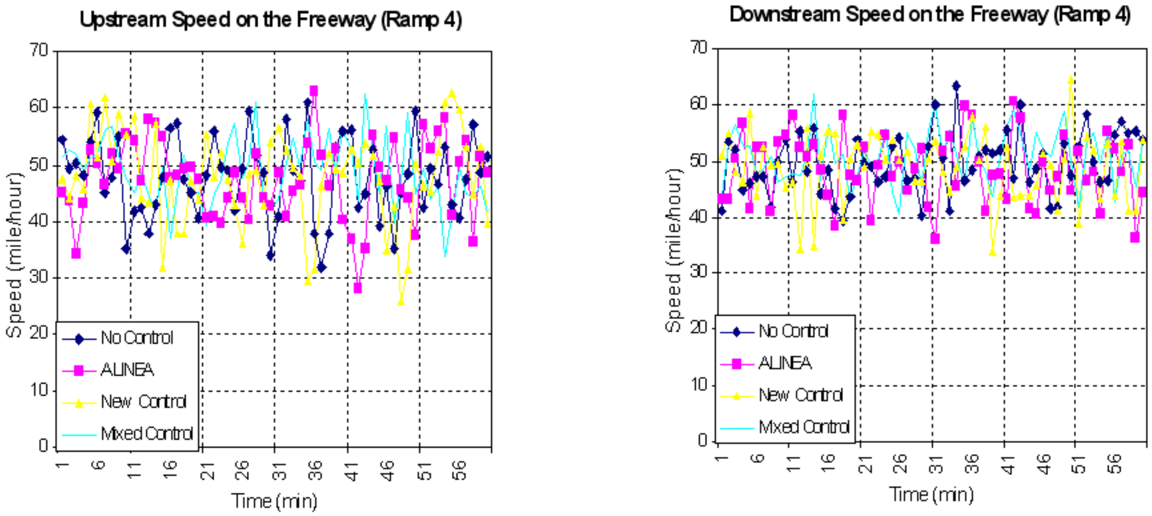


Figure 22. Average time-dependent speed for 3 lanes on upstream and downstream section of ramp 4

The mean densities on the freeway at each intersection are given in Table 14. It is clear that all the ramp control laws made significant improvement to the traffic condition on the freeway at each intersection by keeping the density at lower levels.

Mixed Control provided the largest reduction on the downstream density at the intersections 1 and 4, by 23.11% and 6.21% respectively. Similarly, Mixed Control provided the best results on the upstream density at the same intersections (1 and 2, by 15.52% and 3.85% respectively). As it is observed in Table 14, the improvements at the last intersection were very small compared to improvements on the other intersections due to reasons explained above.

Figure 23 shows the time-dependent density values on the downstream of the freeway. These figures demonstrate that all the controls can make improvements to the freeway conditions.

Table 14. Mean density on the freeway at each intersection (avg. of 3 lanes)

Intersection No	Location	No Con	Alinea	New	Mixed
1	Upstream	28.67	24.38	24.78	24.22
	%change		-14.97%	-13.57%	-15.52%
	downstream	33.8	26.91	26.59	25.99
	%change		-20.39%	-21.32%	-23.11%
2	Upstream	30.89	25.02	24.24	26.74
	%change		-19.00%	-21.52%	-13.42%
	downstream	38.54	32.95	32.57	32.69
	%change		-14.51%	-15.48%	-15.18%
3	Upstream	34.82	26.81	29.66	30.04
	%change		-23.00%	-14.81%	-13.72%
	downstream	41.45	31.63	36.33	36.63
	%change		-23.67%	-12.35%	-11.63%
4	Upstream	38.15	37.92	37.83	36.68
	%change		-0.61%	-0.84%	-3.85%
	downstream	36.62	36.16	37.29	34.34
	%change		-1.25%	1.84%	-6.21%
Average of 4 Intersections		35.37	30.22	31.16	30.92
%change		-	-14.55%	-11.89%	-12.59%

Table 15 depicts the total travel time per car for the main freeway. It can be seen that both New Control and Mixed Control reduced the average travel time on the freeway by about 9%, ALINEA, however, provided the largest reduction in terms of the average travel time on the freeway (10%).

Table 15. Total travel time on the freeway per vehicle

	No Con	Alinea	New Con	Mix Con
in seconds	903.19	815.09	822.82	823.27
in minutes	15.05	13.58	13.71	13.72
% of change		-9.75%	-8.90%	-8.85%

Table 16 demonstrates the total travel time for each ramp (per car). Mixed Control provided the least increase in on ramp travel time (6%) while maintaining optimal flow on the mainline with the help of weight factors for each that are included in the control law. On the other hand, this increase was high for ALINEA and New Control due to the lack of on-ramp queue considerations for these control laws.

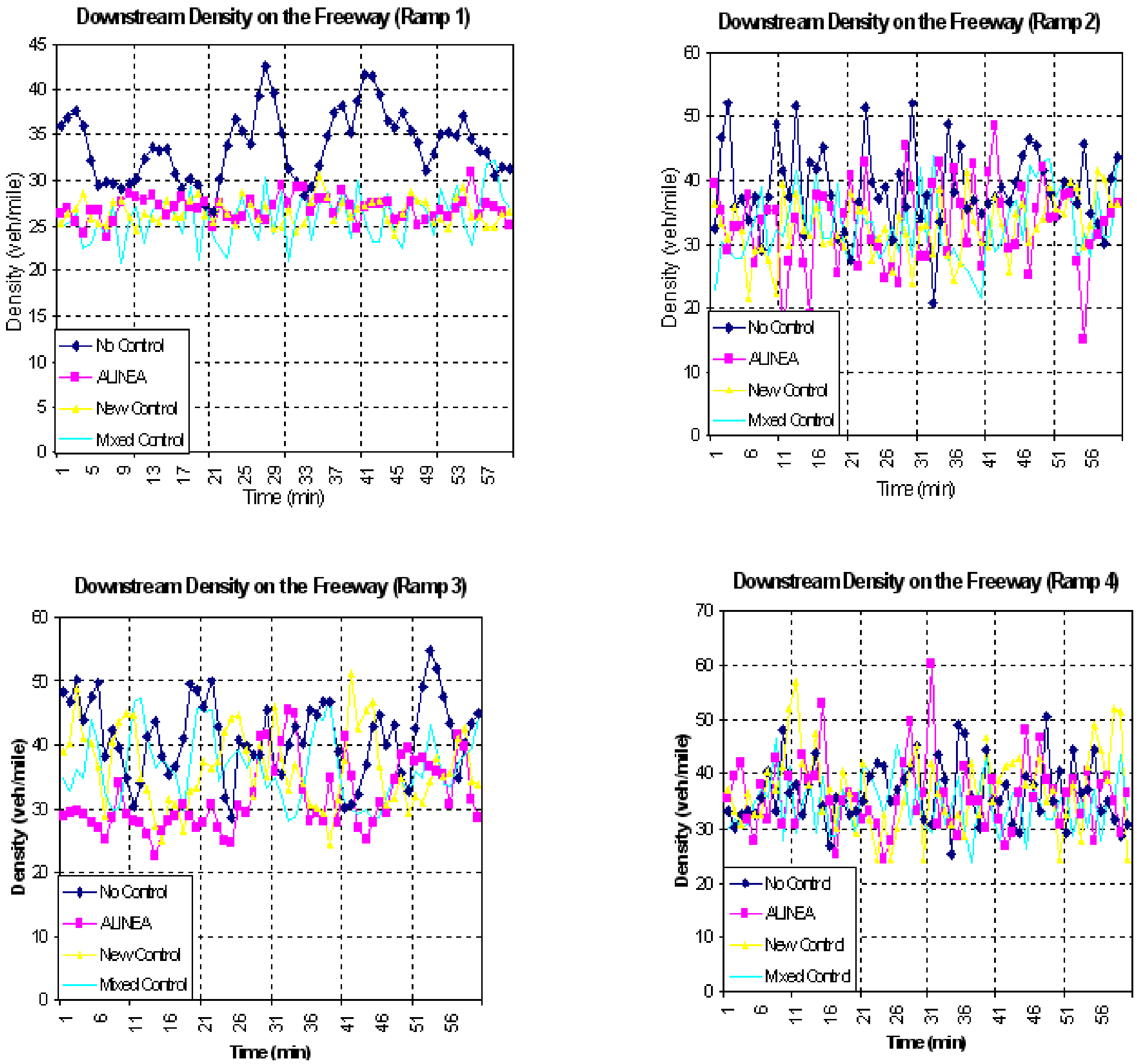


Figure 23. Avg. time-dependent density for 3 lanes on downstream section of ramps

Table 16. Total travel time on the ramp per car (sec)

	No Con	Alinea	New Con	Mix Con
Ramp1	35.40	37.24	45.84	42.61
% of change		5.20%	29.48%	20.37%
Ramp2	91.08	821.00	127.83	95.04
% of change		801.37%	40.35%	4.34%
Ramp3	99.08	815.96	237.20	105.44
% of change		723.51%	139.40%	6.41%
Ramp4	102.57	476.34	147.06	108.86
% of change		364.42%	43.38%	6.13%

In terms of the mainline freeway performance only, the performance of all the ramp control strategies on the mainline appears to be similar. The benefit of ramp metering, measured in terms of total vehicle travel time reduction, is about 9% for all three ramp-metering laws

Table 17 shows the percentage impact of the ramp control strategies on the travel time reduction on freeways. It is observed that all ramp-metering algorithms reduce travel time by some considerable amounts.

Table 17. Travel delay on the freeway (veh.hour)

	No Con	Alinea	New Con	Mix Con
Travel delay	2301.45	2112.89	2089.29	2108.72
% of change		-8.19%	-9.22%	-8.37%

Table 18 shows that Mixed Control provides better results compared to ALINEA and New Control in terms of achieving least increase in ramp travel delay. Mixed Control owes this success to an efficient ramp queue management with the inclusion of on-ramp queue in the control law. ALINEA and New Control, both of which do not consider the on-ramp queue, give priority to freeway traffic but also give some consideration to traffic on entrance ramps when queues on entrance ramps are about to spill back onto surface streets.

Table 18. Travel delay on each ramp (veh.hour)

	No Con	Alinea	New Con	Mix Con
Ramp 1	11.84	12.40	15.29	13.85
% of change		4.76%	29.12%	17.00%
Ramp 2	30.12	224.33	43.13	31.70
% of change		644.88%	43.22%	5.25%
Ramp 3	33.12	216.83	77.09	34.39
% of change		554.70%	132.77%	3.85%
Ramp 4	34.13	144.31	48.68	37.06
% of change		322.81%	42.62%	8.58%
Total Ramp Delay	109.21	597.88	184.19	117.01
% of change		447.47%	68.66%	7.14%

As it is seen in Table 19, Mixed Control provided the best total system-wide improvement by reducing the system travel time by 8% compared to No Control scenario. New Control was also able to counterbalance the decrease of traffic performance on the ramps by the benefits on the mainline freeway. However, in the ALINEA scenario, the improvements on the mainline couldn't overweigh the ramp traffic deterioration; therefore, ALINEA control resulted in 12.45% increase in overall system travel time.

Table 19. Total system (freeway+ramp) delay (veh.hour)

	No Con	Alinea	New Con	Mix Con
Total System (veh.hr)	2410.66	2710.77	2273.48	2225.73
% of change		12.45%	-5.69%	-7.67%

Table 20 depicts the total travel distance on the freeway. The total travel distance was calculated by multiplying the number of vehicles in the system by the total length of the freeway. ALINEA implementation increased the total travel distance on the freeway by 2%, and Mixed Control increased the same measure by 1%, whereas New Control led to decrease in freeway travel distance by 0.35%.

Table 20. Total travel distance on the freeway (veh.mile)

	No Con	Alinea	New Con	Mix Con
Travel distance	100906.67	102652	100551	101431
% of change		1.73%	-0.35%	0.52%

To analyze the on-ramp traffic in detail, on-ramp mean traffic flow values were also compared for all the scenarios (Table 21). It is clear that traffic flow from the on-ramps decreases as a result of ramp metering implementations. However, this decrease was the least for Mixed Control compared with other controls.

Table 21. Total traffic volumes on each ramp

Intersection	No Con	Alinea	%change	New Con	%change	Mix Con	%change
1	742.9	708.69	-0.0461	422.23	-0.4316	546.63	-0.2642
2	699.66	468.46	-0.3304	904.26	0.2924	706.21	0.0094
3	1088.96	537.82	-0.5061	645.36	-0.4074	913.32	-0.1613
4	764.81	543.55	-0.2893	840.69	0.0992	725.75	-0.0511
Total	3296.33	2258.52	-31.48%	2812.54	-14.68%	2891.91	-12.27%

The average length and maximum length of ramp queues are given in Table 22 and Table 23. The queue thresholds are used in ALINEA and New Control strategy to try to prevent the ramps from being overloaded. When queue thresholds are activated, the metering rate switches to the maximum metering rate so that more vehicles can enter the freeway. Queue control is critical to ensure that the ramp delays do not reach unacceptable levels. On the other hand, it leads to reduction in the potential of the freeway control strategy to adjust the metering rates so as to obtain optimized traffic conditions on the freeway.

Table 22. Average length of ramp queue (veh/cycle)

	Ramp 1	Ramp 2	Ramp 3	Ramp 4
No Con	2	3	4	1
Alinea	2	26	33	16
New Con	4	10	25	8
Mixed Con	3	4	3	2

Table 23. Maximum length of ramp queue (veh/cycle)

	Ramp 1	Ramp 2	Ramp 3	Ramp 4
No Con	7	10	7	5
Alinea	8	30	38	19
New Con	11	22	34	17
Mixed Con	9	10	10	8

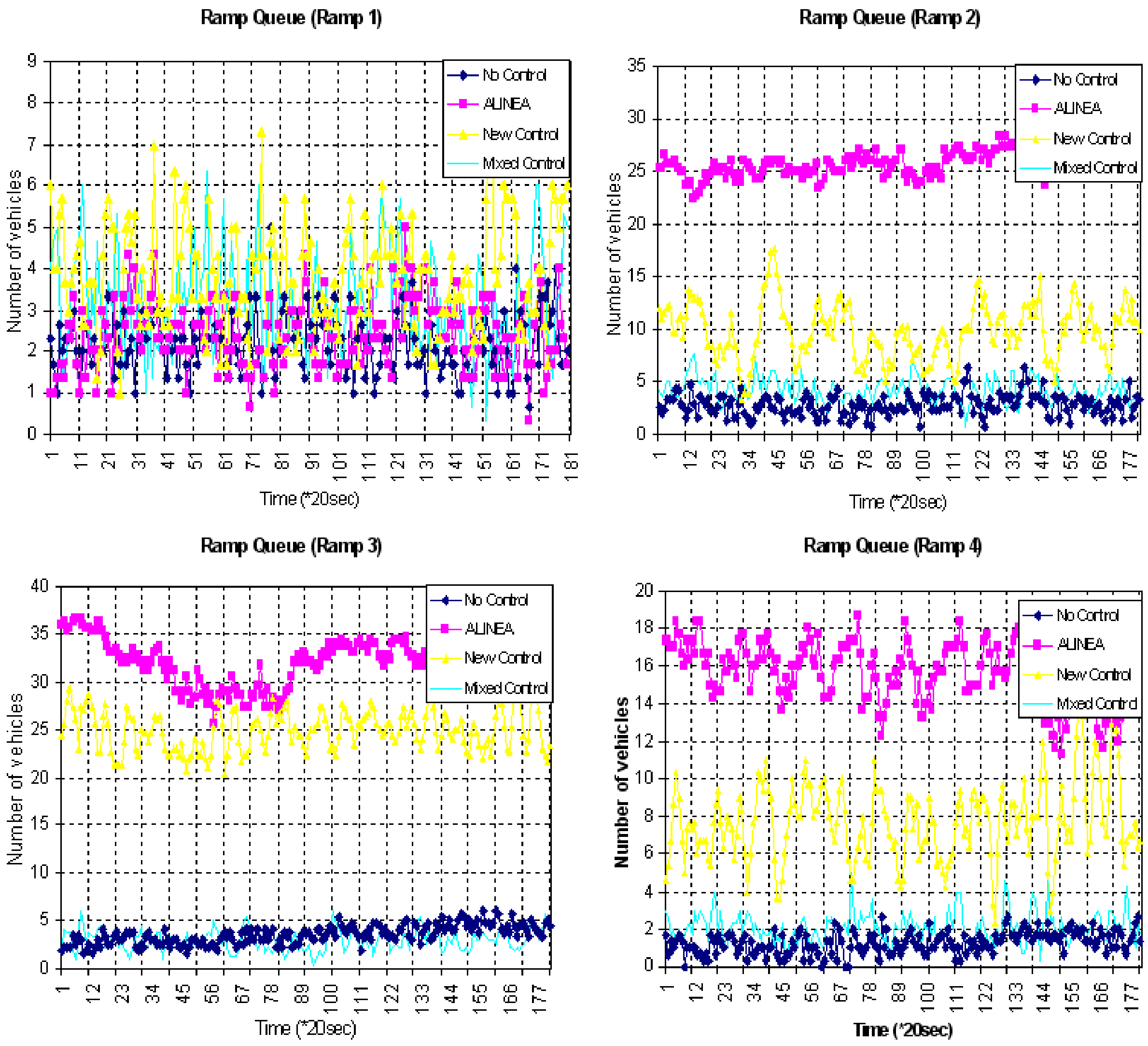


Figure 24. Time-dependent ramp queue plots for each ramp

As observed in Table 22 and Table 23, as well as Figure 24, unlike other controls, Mixed Control provided better management of the on-ramp queues, by acting smoothly before the number of vehicles reaches large values, which might block the arterial network traffic.

The results indicate that the Mixed Control shorten the queue length on the ramp without significant reduction of the freeway throughout. Therefore, with the least increase in ramp travel delay, Mixed Control provided the best total system improvement by reducing the system travel time by 8% compared to No Control scenario.

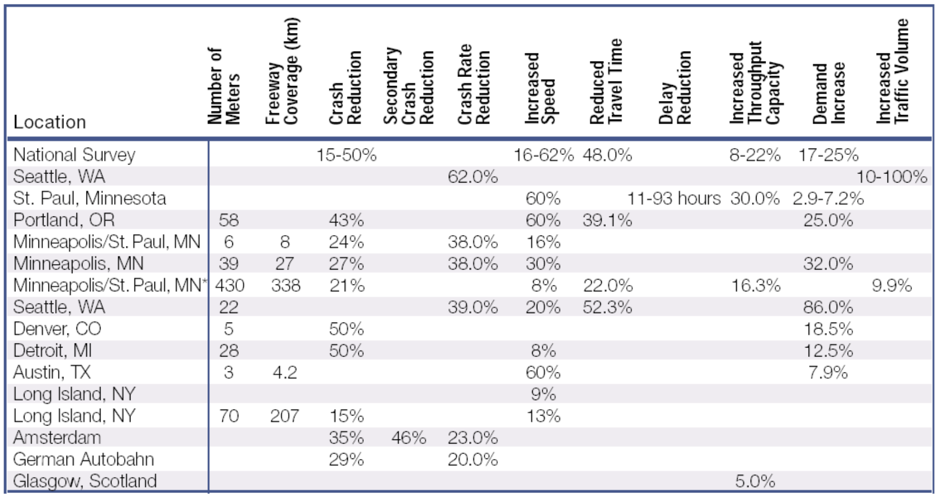
COST BENEFIT ANALYSIS AND CONCLUSIONS

This chapter presents the evaluation of financial feasibility of the two ITS technologies considered in this report, namely simulation based implementation of VMS route guidance and ramp metering technologies in the SJ highway network. The impact of these technologies will be assessed using the simulation results obtained from the calibrated PARAMICS simulation model of the study network.

Specific projects deployed in the United States have shown that ITS technologies on freeway management systems can improve transportation efficiency and generate a multiplier effect in returns on investment (8, 22). Potential impacts of ITS technologies as other transportation investments can be categorized as direct and indirect impacts. Indirect impacts constitute improved business within the area due to the reliability of goods movements and timely deliveries, enhanced regional competitiveness, increase in tourism, etc. Direct impacts of ITS technologies, on the other hand, are reduced travel times, decrease in the number of accidents, and reduced vehicle operating costs. There also exist other external benefits, which are difficult to quantify such as reduction in pollution, safety and emission and noise costs

Most of the available literature demonstrates the positive benefits of ITS technologies in freeway management. This is true both for actual deployments and for analytical studies predicting future benefits. The number of cases reporting negative results is fairly small. It is also recognized that negative impacts may be under-reported in the literature. Much of the collected data have been related to ramp metering. Ramp metering has shown significant reductions in crash rates, and provided increased mainline travel speed. Table 24 outlines much of the ramp metering results collected so far (27). In (27), the analysis of the benefits and costs of the ramp metering system showed that when the costs of the entire congestion management system (including changeable message signs, traveler information, and other components) are factored in, the benefit/cost ratio for ramp metering is 5:1. When ramp-metering benefits are compared to only those costs directly associated with ramp metering, the benefit/cost ratio is 15:1.

Table 24. Summary of ramp metering impacts (27)



Location	Number of Meters	Freeway Coverage (km)	Crash Reduction	Secondary Crash Reduction	Crash Rate Reduction	Increased Speed	Reduced Travel Time	Delay Reduction	Increased Throughput Capacity	Demand Increase	Increased Traffic Volume
National Survey			15-50%			16-62%	48.0%		8-22%	17-25%	
Seattle, WA					62.0%						10-100%
St. Paul, Minnesota						60%		11-93 hours	30.0%	2.9-7.2%	
Portland, OR	58		43%			60%	39.1%			25.0%	
Minneapolis/St. Paul, MN	6	8	24%		38.0%	16%					
Minneapolis, MN	39	27	27%		38.0%	30%				32.0%	
Minneapolis/St. Paul, MN*	430	338	21%			8%	22.0%		16.3%		9.9%
Seattle, WA	22				39.0%	20%	52.3%			86.0%	
Denver, CO	5		50%							18.5%	
Detroit, MI	28		50%			8%				12.5%	
Austin, TX	3	4.2				60%				7.9%	
Long Island, NY						9%					
Long Island, NY	70	207	15%			13%					
Amsterdam			35%	46%	23.0%						
German Autobahn			29%		20.0%						
Glasgow, Scotland									5.0%		

However, it is not always certain that any given ITS technology will work efficiently in any selected priority corridor. This report aims at selecting the best configuration of the considered ITS technology to meet the desired benefits as explained above. Since in every investment decisions, costs and benefits are considered together, here the impact of the selected ITS deployment should surpass the associated costs to justify the deployment of the system.

Cost Benefit Analysis (COBA)

The fundamental effect of transportation investment is to improve travel conditions. The change in travel conditions, in return, affect travel mode choice, route choice, time of travel and destination choice. These choices further affect location decision of households and firms, thus land rent and urban form. They also affect consumers' behavior and firms' production and business decisions. The important question in cost/benefit analysis in every transportation investment, however, is the following. Should the benefits be regarded only as the changes in network travel time, or should changes in land rent, firms' costs and effects from various externalities also be considered in the evaluation? (3)

As mentioned earlier in the report, the evaluation of ITS technologies is based on the selected MOEs. These are (1) total travel time in the network, and (2) route travel times. Although other MOEs can be used to evaluate the network performance, these two MOEs can easily be converted to dollar savings using unit cost values as presented in the literature (21, 23). The indirect impacts of these technologies on the overall productivity in the local economy and the reduction in the external costs such as environmental and accident costs are not considered in this study.

The basic approach in COBA is to attempt to estimate the change in benefits resulting from a proposed action, compared with the "do-nothing" alternative. The differences between these are called "net benefits" and are calculated for each proposed alternatives. The alternative that exhibits the largest net benefit is then selected (28). In this study, the new alternatives are route guidance via VMS and ramp metering and the combination of two technologies. The 'do-nothing' alternative is not to implement any of these two ITS technologies.

The Net Benefits Selection Method

In the case of transportation projects and other investments with a long period of use, the calculation of costs and benefits must include the lifetime of the project. The costs and benefits that are expected to appear in various years throughout the lifetime of the project should be translated into the equivalent value at the present time by discounting. Discounting gives an equivalent value of the future cost or benefit according to the following formula:

$$PV = \frac{1}{(1+i)^t} FV_t$$

Where PV = present value ($)

FV_t = future value at t years from the present time ($)

i = discount rate (%)

In mathematical terms, this method is based upon the calculation of the present value of net benefits for each alternative as follows:

$$NPV_j = B_j - C_j = \sum_{t=0}^{Nj} \frac{1}{(1+i)^t} (B_{j,t} - C_{j,t})$$

where, NPV_j = net present value of net benefits for alternative *j* ($)

i = discount rate (%)

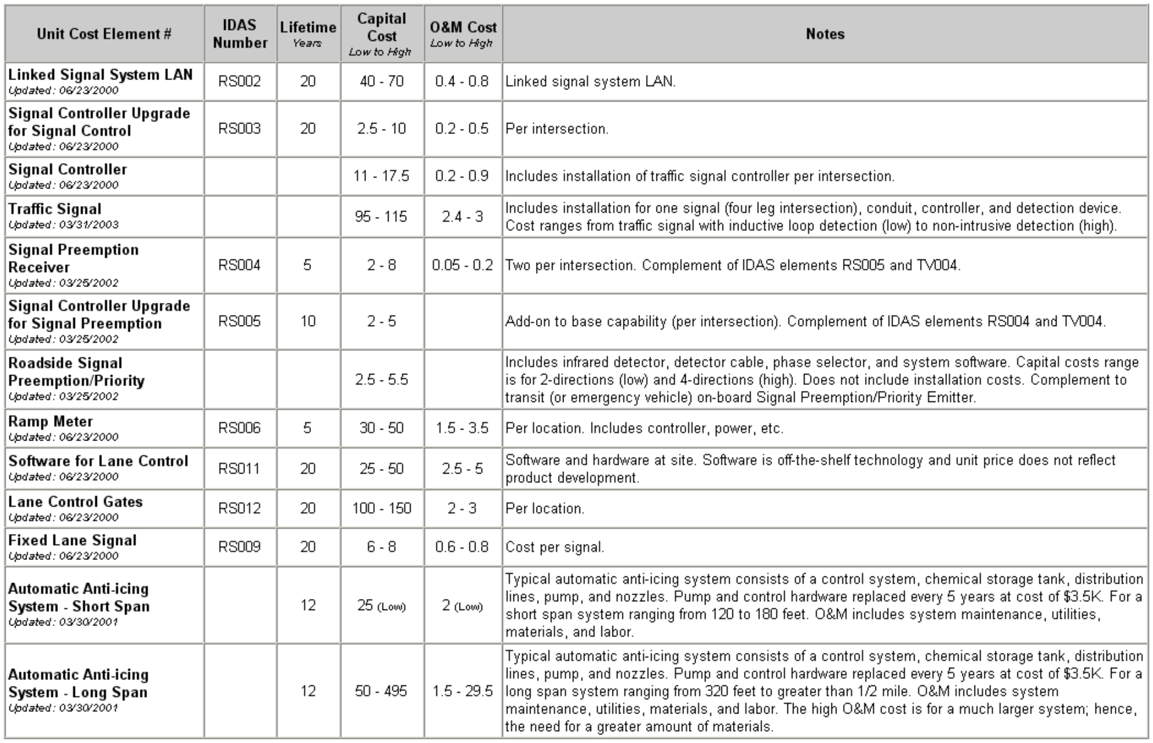
$B_{j,t}$ = benefits of alternative j in time period *t* ($)

$C_{j,t}$ = costs of alternative j in time period *t* ($)

N_j = life-time of alternative *j* (years)

Costs of ITS appear in the capital cost of deploying the system including the detectors, hardware and the equipment, cost of installation, cost of management and operation and operating and improvement costs. Table 25 and Table 26 show the associated costs of various types of equipment used in ramp metering and VMS route guidance systems, respectively.

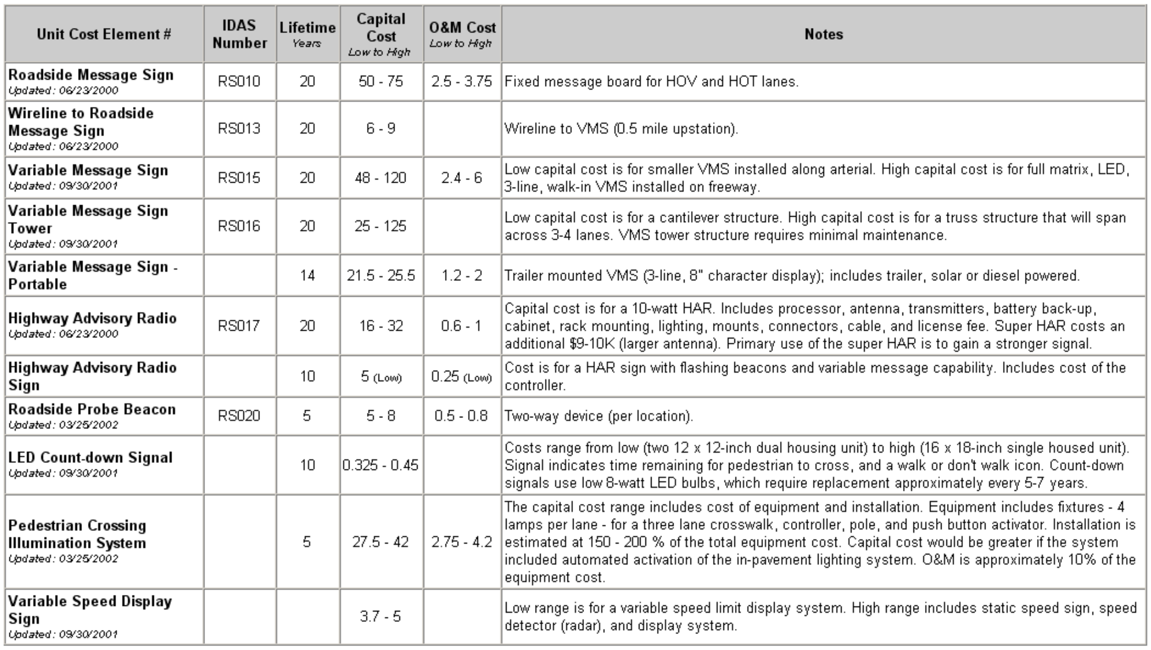
Table 25. Ramp metering costs (27)



Unit Cost Element #	IDAS Number	Lifetime *Years*	Capital Cost *Low to High*	O&M Cost *Low to High*	Notes
Linked Signal System LAN *Updated: 06/23/2000*	RS002	20	40 - 70	0.4 - 0.8	Linked signal system LAN.
Signal Controller Upgrade for Signal Control *Updated: 06/23/2000*	RS003	20	2.5 - 10	0.2 - 0.5	Per intersection.
Signal Controller *Updated: 06/23/2000*			11 - 17.5	0.2 - 0.9	Includes installation of traffic signal controller per intersection.
Traffic Signal *Updated: 03/31/2003*			95 - 115	2.4 - 3	Includes installation for one signal (four leg intersection), conduit, controller, and detection device. Cost ranges from traffic signal with inductive loop detection (low) to non-intrusive detection (high).
Signal Preemption Receiver *Updated: 03/25/2002*	RS004	5	2 - 8	0.05 - 0.2	Two per intersection. Complement of IDAS elements RS005 and TV004.
Signal Controller Upgrade for Signal Preemption *Updated: 03/25/2002*	RS005	10	2 - 5		Add-on to base capability (per intersection). Complement of IDAS elements RS004 and TV004.
Roadside Signal Preemption/Priority *Updated: 03/25/2002*			2.5 - 5.5		Includes infrared detector, detector cable, phase selector, and system software. Capital costs range is for 2-directions (low) and 4-directions (high). Does not include installation costs. Complement to transit (or emergency vehicle) on-board Signal Preemption/Priority Emitter.
Ramp Meter *Updated: 06/23/2000*	RS006	5	30 - 50	1.5 - 3.5	Per location. Includes controller, power, etc.
Software for Lane Control *Updated: 06/23/2000*	RS011	20	25 - 50	2.5 - 5	Software and hardware at site. Software is off-the-shelf technology and unit price does not reflect product development.
Lane Control Gates *Updated: 06/23/2000*	RS012	20	100 - 150	2 - 3	Per location.
Fixed Lane Signal *Updated: 06/23/2000*	RS009	20	6 - 8	0.6 - 0.8	Cost per signal.
Automatic Anti-icing System - Short Span *Updated: 03/30/2001*		12	25 (Low)	2 (Low)	Typical automatic anti-icing system consists of a control system, chemical storage tank, distribution lines, pump, and nozzles. Pump and control hardware replaced every 5 years at cost of $3.5K. For a short span system ranging from 120 to 180 feet. O&M includes system maintenance, utilities, materials, and labor.
Automatic Anti-icing System - Long Span *Updated: 03/30/2001*		12	50 - 495	1.5 - 29.5	Typical automatic anti-icing system consists of a control system, chemical storage tank, distribution lines, pump, and nozzles. Pump and control hardware replaced every 5 years at cost of $3.5K. For a long span system ranging from 320 feet to greater than 1/2 mile. O&M includes system maintenance, utilities, materials, and labor. The high O&M cost is for a much larger system; hence, the need for a greater amount of materials.

In this report, a net-present value comparison is utilized to determine whether the proposed ITS technology should be selected for implementation. The net-present value comparison requires the values of these costs and benefits at different points in the projected lifetime of the project. With the use of a discount rate costs these costs/benefits can be shifted back to the present time and the implementation of the proposed system can be evaluated using the estimated net-present value.

Table 26. VMS route guidance costs (27)



Unit Cost Element #	IDAS Number	Lifetime *Years*	Capital Cost *Low to High*	O&M Cost *Low to High*	Notes
Roadside Message Sign *Updated : 06/23/2000*	RS010	20	50 - 75	2.5 - 3.75	Fixed message board for HOV and HOT lanes.
Wireline to Roadside Message Sign *Updated : 06/23/2000*	RS013	20	6 - 9		Wireline to VMS (0.5 mile upstation).
Variable Message Sign *Updated : 09/30/2001*	RS015	20	48 - 120	2.4 - 6	Low capital cost is for smaller VMS installed along arterial. High capital cost is for full matrix, LED, 3-line, walk-in VMS installed on freeway.
Variable Message Sign Tower *Updated : 09/30/2001*	RS016	20	25 - 125		Low capital cost is for a cantilever structure. High capital cost is for a truss structure that will span across 3-4 lanes. VMS tower structure requires minimal maintenance.
Variable Message Sign - Portable		14	21.5 - 25.5	1.2 - 2	Trailer mounted VMS (3-line, 8" character display); includes trailer, solar or diesel powered.
Highway Advisory Radio *Updated : 06/23/2000*	RS017	20	16 - 32	0.6 - 1	Capital cost is for a 10-watt HAR. Includes processor, antenna, transmitters, battery back-up, cabinet, rack mounting, lighting, mounts, connectors, cable, and license fee. Super HAR costs an additional $9-10K (larger antenna). Primary use of the super HAR is to gain a stronger signal.
Highway Advisory Radio Sign		10	5 (Low)	0.25 (Low)	Cost is for a HAR sign with flashing beacons and variable message capability. Includes cost of the controller.
Roadside Probe Beacon *Updated : 03/25/2002*	RS020	5	5 - 8	0.5 - 0.8	Two-way device (per location).
LED Count-down Signal *Updated : 09/30/2001*		10	0.325 - 0.45		Costs range from low (two 12 x 12-inch dual housing unit) to high (16 x 18-inch single housed unit). Signal indicates time remaining for pedestrian to cross, and a walk or don't walk icon. Count-down signals use low 8-watt LED bulbs, which require replacement approximately every 5-7 years.
Pedestrian Crossing Illumination System *Updated : 03/25/2002*		5	27.5 - 42	2.75 - 4.2	The capital cost range includes cost of equipment and installation. Equipment includes fixtures - 4 lamps per lane - for a three lane crosswalk, controller, pole, and push button activator. Installation is estimated at 150 - 200 % of the total equipment cost. Capital cost would be greater if the system included automated activation of the in-pavement lighting system. O&M is approximately 10% of the equipment cost.
Variable Speed Display Sign *Updated : 09/30/2001*			3.7 - 5		Low range is for a variable speed limit display system. High range includes static speed sign, speed detector (radar), and display system.

Benefits of VMS Guidance

In Chapter 3, the VMS route guidance was simulated in the study corridor and the feasible locations of VMS structures were determined in terms of the selected MOEs. The change in average route travel time is a very effective measure for capturing the impact of the proposed technology along the main route. However, in the COBA analysis we use the total network travel time instead of route travel time to calculate the net benefits of the selected ITS technology. This is due to the fact that the study corridor is not comprised of the analyzed route only. Hence the impact of the proposed system should be evaluated for the whole system. For example, as mentioned earlier, ITS technologies have wider effects beyond the highway section they are implemented. For example, ramp metering effectively coordinated with arterial signals can relieve congestion on the freeways as well as on local roads. On the other hand, queue spill over onto the arterial street as a result of ramp metering, can create unexpected congestion on the local roads.

Several assumptions are made throughout the cost benefit analysis of VMS guidance.

These are given as follows:

- VMS route guidance is necessary during non-recurrent congestion such as incidents, short-term roadwork, and adverse weather conditions, etc. Thus, the benefits of VMS guidance are estimated only when VMS is needed. In Chapter 3, the feasible locations of VMS structures were determined based on a 20-minute accident on I-76. NJDOT accident database reports that along the mainline of the study corridor (I-76 and I-676), there were 152 accidents reported in the year 2000 (29). This statistic shows that on average every two days there is an accident along the main highway in our study network.[5] Although each accident has different duration and impact on the mainline traffic, it is impossible to take into account each particular type of accident due to the limited scope of this study. It is known that most accidents on all highways are minor accidents (32). Therefore, our assumption of 20 minutes accident duration in our simulation analyses was justifiable
- However, not all the accidents cause traffic delays. Most accidents involve stalled vehicles and do not impede the traffic flow if there is enough shoulder width. Thus, it is assumed in the analysis that the number of accidents causing traffic delay during the peak period is between 20 and 40 per year
- Benefits are estimated for a time period of 5 years using a 6% discount rate
- Value of time is assumed to vary between \$5 and \$9 per hour

To estimate the benefits of VMS guidance in the study corridor, results presented in chapter 3 are used here. It was found in the simulation analysis that VMS 1, VMS 2, VMS 3 and VMS 2&3 in Figure 9 performed feasible network wide results. The percentage improvements in the average network travel times are presented in Table 3. Table 27 shows the estimated benefits of each successful VMS scenario based on the assumptions listed above.

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[5] This assumption clearly disregards multiple accidents at the same time period.

Table 27. Benefits of VMS route guidance in the study network

VMS Scenarios	Total Travel Time Savings (hours)*	Monetarized Travel Time Savings ($)	Annual Estimated Benefit Range ($)**	Present Benefit ($)**
VMS 1	1013.3	5067.0 – 9120.0	101,300 - 364,800	426,700 - 1,536,600
VMS 2	1656.0	8280.0 – 14900.0	165,600 - 596,100	697,500 – 2,511,000
VMS 3	962.6	4813.0 - 8664	96,260 - 346,560	405,500 – 1,460,000
VMS 2 & 3	1444.0	7220 – 13000.0	144,400 - 520,000	608,250 – 2,190,500

* Calculated by multiplying the average network travel time savings by the total number of vehicles in the network during a given peak period

** The benefit range is due to the assumed accident occurrence rate

Benefits of Ramp Metering

To estimate the feasibility of ramp metering strategies in the study corridor, 4 locations have been selected for these analyses among the possible locations suggested in (39). The corridor chosen for the study has 11 on-ramps on northbound, at 4 of which local feedback ramp metering strategies, namely ALINEA and Mixed Control are implemented (See RAMP METERING STRATEGIES section for a detailed discussion of these control algorithms). Figure 25 shows the schematic view of the location of the controlled on-ramps. The freeway sections upstream and downstream of the ramp consist of 3 lanes for the first three on-ramps, with 1 lane on the ramp. For the seventh on-ramp, the upstream freeway section has 4 lanes and the downstream freeway section has 5 lanes with 1 lane on the ramp.

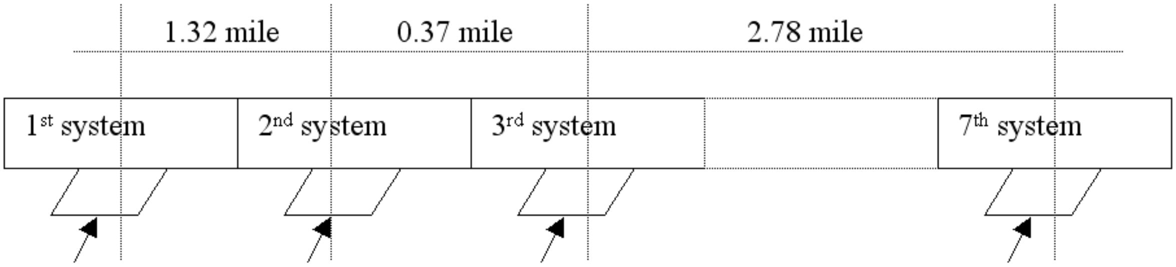

Figure 25. Distance of controlled on-ramps on the corridor

The effectiveness of a ramp control strategy can be evaluated based on a number of different performance measures. Some are based on throughput whereas others are based on travel time or delay. Nevertheless, it is important to look at these two performance measures together to get a real sense of the system-wide benefits of the ramp metering implementations. For example, an increased number of vehicles is likely to lead to increased total vehicle hours. However, increased vehicle hours do not necessarily show degradation in system performance since average vehicle travel time can be equal to or less than what it was before the implementation of ramp metering, however a significant increase in the vehicles using the system can increase the total vehicle hours. On the other hand, all relevant MOEs together can give a better picture of the system's performance.

MOEs that can be used to evaluate ramp-metering algorithms are the following:

- Vehicle-hours traveled, which is a measure of overall system performance for the entire network obtained from the simulation analysis
- Average network travel time, which is a measure of traffic conditions on the entire network
- Throughput, which is the number of vehicles served at a link
- Average downstream occupancy
- Average and maximum on-ramp queue

As already mentioned earlier, travel time is the most useful measure in COBA. The MOEs listed above are useful in evaluating the system performance; nevertheless average network travel time is the only MOE that can be converted into monetary units to be included in COBA.

The assumptions in the estimation of ramp metering benefits are given as follows:

- Ramp metering is effective during the congested periods and when there is no interruption in traffic flow such as incidents. If traffic flow comes to a halt because of an incident, the ramp control will hold the vehicle release at the ramps at a minimum. In this case, a queue spillover onto the arterials will be inevitable. Thus, in the cost benefit analysis, benefits of ramp metering in the study network are estimated only during uninterrupted traffic flow

- It is assumed that the annual estimated benefit is simply the number of peak hour periods during a year on the selected traffic movement direction
- The number of commuting days is assumed to vary between 250 days per year
- Benefits are estimated for a time period of 5 years using a 6% discount rate
- Value of time is assumed to vary between $5 and $9 per hour.

Table 28 shows the estimated benefits of each ramp metering control algorithm using the simulation results of the study network based on the above listed assumptions.

Table 28. Benefits of ramp metering in the study network

Ramp Metering	Total Travel Time Savings (hours)	Monetarized Travel Time Savings ($)	Annual Estimated Benefit Range ($)*	Present Benefit
ALINEA	220.62	1103.0 – 1986.0	275,700- 496,400	1,161,000 – 2,100,00
MIXED CONTROL	885.05	4425.0 – 7965.0	1,106,300 - 1,991,400	4,660,000 – 8,388,400

*This column is calculated by multiplying the travel time savings column by 250 days.

In Table 27 and Table 28, the benefits of VMS route guidance and ramp metering are presented within a range of values. We believe that the costs and benefits of these technologies should not be presented by fixed values. Uncertainties always exist due to many underlying assumptions in COBA.

Results and Conclusions

The costs of ramp metering and VMS routing vary according to the desired function of these technologies and the location. Especially installation and maintenance costs of ramp metering can vary considerably depending on the level of the technology and the number of units used. However, it should be mentioned that the cost of implementing these technologies are not only equipment costs. It includes planning and design, markup costs and labor costs. The cost of ramp metering can be broken down to **metered ramp construction** (includes the construction cost for improving on-ramps to support ramp metering), **metered ramps with signals** (includes detection and signals associated with ramp metering) and **operation and maintenance** (20). Varying cost estimates of ramp metering reported in the literature. Kang and Gillen (20) reports several ramp metering cost estimates from the literature as shown in Table 29. Assuming that the lifetime of ramp metering is 5 years and the discount rate is %6, the net present cost of implementing a single ramp metering is given in the last row of Table 29. The larger difference between these attributes can be contributed to the extent of roadwork, as well as the irrigation and drainage required for each specific ramp. Some of the reported estimates in the literature represent the costs of installing a single ramp metering and some of the costs represent a percentage of a freeway construction.

Table 30 shows the range of equipment costs of each proposed alternative derived from Table 25 and Table 26 with assumed quantity of the required equipment. The number of detectors required for VMS guidance is assumed to vary between 10 and 16 detectors. Also, for ramp metering the number of detectors needed for ALINEA and Mixed Control algorithms are 2 and 4 detectors, respectively. These figures do not include the planning and administration costs, communication costs, markup costs, etc.

Table 29. Cost estimates of ramp metering (20)

	Case 1	**Case 2**	**Case 3**
Installation & Construction Cost	750,000	300,000	113,000
Annual Maintenance Cost	75,000	30,000	2,200
Net Present Cost	1,066,000	426,400	122,250

Since the cost figures from each source vary substantially, in our analysis we assume the range $135,000 - $425,000 for the present cost of installing ramp metering regardless of the control algorithm used. As for VMS routing costs, we use a range of $100,000 - $ 325, 000 of net present cost values in the cost benefit analysis.

Table 30. Equipment cost for VMS route guidance and ramp metering

	Equipment	Quantity	Unit Capital Cost	Unit Maintenance Cost	Lifetime	Total Present Cost of Equipment
VMS Route Guidance	VMS	1	48 – 120	2.4 – 6.0	20 years	98.3 – 277.2
	Wireline		6 - 9	-	-	
	Detector	10 - 16	3 - 6	0.1 – 0.4	10	
Ramp Metering	Ramp Meter	1	30 - 50	1.5 – 3.5	5	154.3 – 223.1
	Traffic Signal	1	95 - 115	2.4 – 3.0	-	
	Detector	2 - 4	6	0.1 – 0.4	10	

Note: All costs are in $K

Table 31 summarizes the costs and benefit ranges of each alternative scenario for VMS route guidance and ramp metering.

Table 31. Cost Benefit analysis results of proposed alternatives

Scenarios	Present Benefit	Cost	Net Present Benefit	B/C Ratio
ALINEA	1,161 – 2,100	540-1700	-539.0 – 1,560.0	0.68 - 3.88
MIXED CONTROL	4,660 – 8,388	540-1700	2,960.0 – 7,848.0	2.74 – 15.53
VMS 1	427 - 1,537	100-325	102.0 - 1,437.0	1.31 – 15.37
VMS 2	697 – 2,511	100-325	372.0 – 2,411.0	2.14 – 25.11
VMS 3	405 – 1,460	100-325	80.0 -1,360	1.25 – 14.60
VMS 2&3	608 – 2,190	100-325	283.0 – 2,090.0	1.87 – 21.90

Note: All costs are in $K

The benefit / cost ratios given in Table 31 are more than 1.0 except in ALINEA control (Although the cost of ramp metering for 4 on-ramps is calculated by multiplying the assumed ramp metering cost by 4, it should be less than $540,000 - $1,700,000 range due to scale economies). However, these results are very much dependent on the underlying assumptions. Nevertheless, most of the ramp- metering results are in accordance with the results given in the literature. As mentioned earlier in the chapter, in (27) the benefit cost ratio of ramp metering is reported as 15:1.

It can be concluded that ITS technologies yield benefits when they are selected logically and deployed with knowledge of their performance tradeoffs. The benefits can easily surpass the costs of implementing these technologies if the existing level of highway performance is very poor. There are also other benefits of ITS technologies where there are not clear travel time savings benefits such as reduced stress, reduced number of accidents, increased traffic throughput, greater reliability in travel times, non-traveler benefits, agency benefits, and environmental benefits (reduced air pollution). For example, ramp metering is also effective in reducing the number of accidents on the mainline. In a recent project by Minnesota Department of Transportation, 430 ramp meters were shut down for 6 months to evaluate the impacts associated with the ramp meters. The results from this project indicated that there was 26% increase in crashes, which included a dramatic 200% increase in sideswipe crashes. In a similar project by Washington State Department of Transportation, traffic engineers observed that ramp metering reduced rear end and sideswipe accidents by more than 30%. Also, (40) conducted a survey of ramp metering safety benefits in North America, the accident reduction percentage ranges between 15% and 50%. Similarly, in Arizona, a study was conducted to observe the effect of ramp metering on accident reduction and it was concluded that ramp metering has positive effect on accident reduction. These statistics reveal that ramp metering is effective in minimizing speed disruption and accident risks at merge points. Such important benefits warrant further research on ramp metering.

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