PACKETS, ROUTERS, AND AUTOMOBILES: WHAT CAN DATA NETWORKS TEACH US ABOUT TRAFFIC CONGESTION?

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On my honor as a University student, on this assignment I have neither given nor received unauthorized aid as defined by the Honor Guidelines for Papers in TCC Courses.

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ABSTRACT

This project applied data network congestion control and avoidance techniques to freeway systems through simulation and measured their effectiveness. Experimentation revealed that Fair Queueing at the most congested on-ramps combined with the addition of a lane to the freeway provided the most significant improvements to the freeway system. This finding is significant because it demonstrates potential for the cross-application of data network congestion control techniques to congested freeways.

Data networks and freeway systems are similar in several ways. Both systems allow for the flow of information or vehicles along limited pathways and have distinct entry points that are capable of flow rate metering. There are differences between the systems, however, that make cross-application somewhat difficult. Traffic networks are generally centralized systems where current congestion data is readily available, while large-scale data networks are decentralized, making monitoring considerably harder, and requiring additional guesswork. Additionally, data networks usually prevent data entry into the system when congestion gets particularly bad, whereas such a flow shutdown at a freeway on-ramp would be unacceptable. Despite these differences, in the simulations conducted for this project data network congestion control techniques often increased throughput and capacity and reduced travel time on freeway systems, though at the cost of increased wait times at freeway on-ramps. Solutions to this wait problem include alternate routes, parallel freeways, and toll roads pro-rated for current wait time.

It is my hope that the research described in this report will promote collaboration between two similar areas of research - data network and freeway system congestion resolution. Such sharing would greatly benefit both research areas.

1. Introduction

1.1 Purpose Statement

This project evaluated the effects of applying data network congestion control and avoidance techniques to limited access highway systems through simulation. It measured the ability of each technique to decrease travel time and increase throughput and capacity in traffic systems while avoiding unacceptably long wait times at freeway on-ramps. The results showed that Fair Queueing at the most congested on-ramps combined with the addition of a lane to the freeway provided the most balanced improvement to the freeway system, and demonstrated potential for the cross-application of data network congestion control techniques to congested freeways.

1.2 Problem Definition and Background

In upstate New York, nearly 90 percent of personal travel is by motor vehicle. This is because, as in many regions of America, people prefer to travel in private vehicles as opposed to public forms of transportation. Even in downstate New York, where an extensive public transportation system exists in both New York City and Long Island, the percentage is still 57 percent, greater than half of all personal travel. A politician could win a local election on the platform of reducing traffic congestion. Across the nation, according to survey results published by Kenneth Orski and cited by Levy and Bragman, "traffic congestion has superseded crime, housing, and unemployment as the primary concern of voters" [1].

For many years, engineers have been developing analytical models and simulation tools to study and improve vehicular flow on highways. Such methods give us a better understanding of vehicular and traffic system behavior. Forty years ago, Herman and Gardels [2] developed a mathematical model of traffic. They used it to invent a technique they called platooning, which increased traffic flow in the Holland Tunnel that connects New York and New Jersey. Today, there is an entire branch of engineering devoted to predicting and improving traffic flow on roadways.

More recently, computer engineers and computer scientists have been developing ways to improve data network traffic flow and efficiency, primarily with sophisticated congestion control and avoidance techniques. In particular, they have focused on improving the Transmission Control Protocol (TCP) [3], which the Defense Advanced Research Projects Agency developed in 1981, and which is now the dominant reliable protocol used in the transmission layer of the Internet [4]. Such networks have much in common with a freeway system, and with a basic traffic model. A data network allows for flow of information along limited pathways, and entry of data packets at discrete points within the system. Similarly, limited access highways limit the flow of traffic to their road surface, and restrict entry to specified on-ramps. One difference between the two systems, however, is that freeway systems are generally more centralized, with ownership and control of the system falling under a single authority, such as a state Department of Transportation. This allows a congestion control technique to take measurements that will conclude definitively if congestion exists on the freeway. Large-scale, decentralized data networks do not have this luxury, and determination of congestion requires estimation and guesswork. Another difference is that data networks typically shut down flow at entry points in the system when congestion gets particularly bad, whereas such metering behavior at a freeway on-ramp would be unacceptable.

This report discusses the outcomes of applying data network congestion control and avoidance techniques to a simulated vehicular traffic system. Despite the differences between vehicular traffic and data networks, data network congestion control techniques had a considerable impact on freeway systems in the simulations conducted for this project. The techniques often increased throughput and capacity and minimized travel time, though at the cost of increased wait times at freeway on-ramps. The technique that best applied to the system, and was most practically adaptable to the real world in the right situations, was Fair Queueing at highly congested on-ramps combined with the addition of a lane to the freeway. This project also demonstrated that physical vehicles on a roadway often respond to the same congestion control and avoidance techniques as abstract data packets on a communications line.

1.3 Scope and Method

I tested the effects of approximately ten congestion control and avoidance techniques, and some of their combinations, in a simulated traffic system environment. Most of these techniques are applied by means of on-ramp meters in the simulation. The tests measured how the applied techniques altered the flow, capacity, and travel time on the freeway.

I considered three general categories of techniques based on their strategy for controlling congestion. The first category contains techniques that restrict the flow of new data packets into the network in an attempt to prevent network overload. This category of techniques was applied to the simulation through on-ramp metering. The second category contains techniques that drop packets already present in the network, usually when the packet traffic in the network exceeds a certain threshold. On-ramp metering was also used to apply these techniques, substituting a metering restriction for a vehicle "drop" (which is impossible). Therefore, these techniques when cross-applied actually became much like the first category, controlling congestion at the entry points of the system instead of internally. Finally, I placed techniques that used alternate methods for increasing the flow and efficiency of the network in the last category. These techniques required a different approach when applied to the simulated freeway.

1.4 Overview of Report

The remainder of this report will provide some technical background, and then proceed to describe the experiment and its results. Chapter 2 provides an overview of data network congestion control techniques and traffic flow control research, along with a comparison of data networks and freeway systems. Chapters 3 through 5 then describe the project work itself. Chapter 3 discusses the creation of the real-world freeway simulation on which the experiment is performed. Chapter 4 outlines the procedures for applying each technique separately to the freeway simulation, and discusses the results, including an explanation of what constitutes a successful technique. Chapter 5 presents the results of testing combinations and improvements of the congestion resolution techniques, and an evaluation of most successful combination, Fair Queueing at three on-ramps combined with the addition of a lane to the freeway. Finally, chapter 6 concludes with a summarization of the experiment, interpretation of the results, and recommendations for future research in this area.

2. DATA NETWORKS AND TRAFFIC SYSTEMS OVERVIEW AND COMPARISON

2.1 Overview of Data Networks

Before discussing the ways in which data networks control and avoid congestion, some background on data networks is needed. One can view a data network as a collection of links and nodes. Nodes send data across the links, which provide connectivity and allow nodes to share data with one another. Additionally, a set of cooperating nodes can achieve indirect connectivity amongst themselves. Nodes accomplish this by allowing data en route to a destination to be forwarded through them. In other words, nodes agree to serve as intermediate nodes in the data path from the source to the destination. Such cooperating groups of nodes can be interconnected with other groups to form a scalable internetwork. The interconnecting component is usually a router or gateway, a simple node that forwards data from one cooperating group of nodes to another. The Internet gets its name from the fact that it has this internetwork structure. The nodes in the network are usually computers, routers, or gateways, while the links in the network generally refer to some physical medium that connects two or more nodes [4]. As an example of a network, consider Figure 2.1.

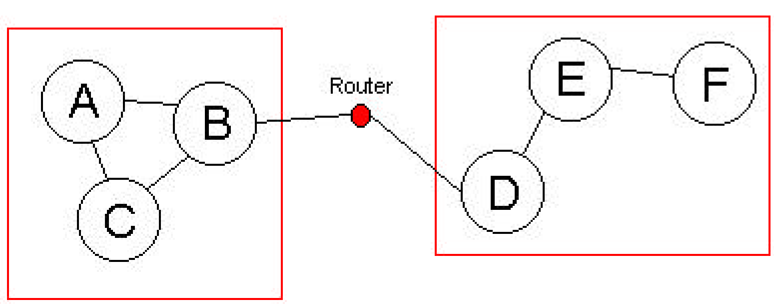

Figure 2.1 - A Simple Interconnected Network

In a network without indirect connectivity, nodes would only be able to communicate with their neighbors. Node D would only be able to share data with node

E, and node A would only be able to share data with nodes B and C. If nodes D, E, and F cooperate, however, D can establish indirect connectivity with node F. Additionally, if nodes A, B, and C choose to cooperate, both cooperating groups of nodes can be interconnected through an external router to form the simple internetwork shown in Figure 2.1.

To guide the design and implementation of a network, a data network system designer typically refers to a layered network architecture. This allows for progressively higher and more abstract levels of service in each layer. The most popular theoretical model, known as the Open Systems Interconnection (OSI) architecture, defines seven layers of abstraction, from the physical connection layer to the application layer. The most important layers for the purposes of this report are the second and fourth layers. The second layer is the data link layer, which handles the transmission of streams of data bits. The Ethernet protocol, a widely used local area networking technology, operates in this layer. The fourth layer is the transport layer, which handles transmission of data messages (generally a number of data packets, or blocks of data) between nodes. The Transmission Control Protocol (TCP) [3] operates in this layer. This is one level of abstraction above the network layer, which handles the successful delivery of individual data packets. This is the layer in which the most widely used network layer protocol today, the Internet Protocol (IP), operates [4].

2.2 Network Congestion Control and Avoidance Techniques

There are a number of congestion control and avoidance techniques available to reduce congestion, increase packet flow, and reduce round-trip times in data networks.

Many of these techniques are designed to work with the Transmission Control Protocol (TCP) [3], the dominant reliable protocol used in the transmission layer of the Internet [4]. TCP controls network congestion by altering the rate at which an end point sends packets into the network. TCP does this by limiting entry of data into the network with a congestion window. A congestion window permits the source to send a number of packets, or segmented blocks of data, equal to the current size of the congestion window. TCP controls how much data can enter the network at a given time through manipulating the size of this window. Most of the congestion control and avoidance techniques for TCP set the size of the window based on feedback from the network. This feedback is usually in the form of acknowledgements that are sent from the receiver to the sender to indicate successful packet delivery. Oftentimes, the techniques assume that "lost" packets (packets for which the source does not receive an acknowledgment) indicate congestion and act accordingly to reduce it [4].

2.2.1 Network Entry-Point Techniques

The first category of techniques are those that restrict the flow of packets into a data network, usually with a congestion window. All of these techniques handle congestion at the endpoints of a network, that is, where new data is waiting to enter.

Most data networks provide their lowest level of congestion control at the data link layer, where the Ethernet protocol often operates. This protocol implements two simple forms of congestion control in its transmitter algorithm. When the line is idle, the protocol transmits a frame (similar to a packet) immediately. When the line is busy, however, the algorithm waits until the line is idle and then transmits with a probability p.

This is known as p-persistence, and Ethernet networks use it to prevent multiple adapters from trying to transmit at the same time when the line becomes free, to prevent collisions. If two adapters transmit at the same time anyway, their data collides and this stops transmission. These adapters then wait a certain amount of time and try again. Each time the transmission fails, an adapter increases its wait time (usually doubling it) before trying again. This is known as exponential backoff, and it is the other form of congestion control in an Ethernet [4].

In 1988, Jacobson and Karels [7] suggested several modifications to the then-current implementations of the TCP protocol. Their primary philosophy was that packet flow on a TCP connection should be conservative in order to avoid congestion collapse. An overflow of packets into the network causes this collapse, which results in a sudden drop in data throughput through the network. This drop is often crippling to the network, as demonstrated by the "factor-of-thousand drop" cited in the paper [7]. Today, TCP implements most of the modifications proposed in the paper, including Additive Increase/Multiplicative Decrease (AIMD) and a slow-start algorithm that gradually increases the number of packets sent. The paper also included a discussion of estimating packet round-trip times in data networks. This laid the groundwork for a congestion avoidance scheme known as TCP Vegas, which capitalizes on round-trip-time estimation calculations in a way that will be described later.

AIMD interprets a "lost" packet as congestion, and responds by halving the size of the congestion window. Every successful transmission increases the size of the congestion window by one packet, in a conservative attempt to take advantage of the available capacity of the network [4].

Slow-Start [7] is a refinement of AIMD that allows the source to reach the operating capacity of the network much faster, while preventing a "burst" of packets into the network that could cause congestion. This technique initially increases the size of the congestion window exponentially rather than linearly after every successful transmission. This behavior continues until there is a packet "loss" or the congestion window size reaches a given capacity threshold, at which point the congestion window is halved (if a "loss" occurred) and AIMD takes over [4].

TCP Vegas uses round-trip-time (RTT) estimation [7] and the current sending rate to modify the congestion window in an effort to avoid congestion before it occurs. It uses the RTT and congestion window size to calculate an expected transfer rate (when the network is not congested), which it then compares to the current sending rate. The algorithm increases the congestion window linearly when the difference between the current sending rate and the expected rate is small, which it interprets as under-utilization of the network. Similarly, it interprets a large difference between the two rates as over-utilization of the network, and decreases the window linearly in response [4].

Other congestion avoidance schemes involve the network routers as well as the entry points of the network. Routers are intermediate nodes in the network that forward data from its source to its destination. In the DECbit [4] congestion avoidance scheme, routers monitor the load they are experiencing and must set a "congestion bit" in their packets if they detect congestion. They assume the network is congested if their average queue length (number of packets waiting to be forwarded at the router) is greater than or equal to one. Packets with their "congestion bit" set eventually reach the destination node. The destination node then informs the source node that the "congestion bit" was set when it sends its acknowledgement. The source node uses this information to avoid congestion. If less than 50% of the packets it sent had the "congestion bit" set, then it increases its congestion window by one. Otherwise, it decreases the congestion window by one-eighth of its previous value.

A recent paper proposes a modification to TCP AIMD for certain applications called Friendly Rate Control (FRC) [8]. The philosophy behind FRC, according to the authors of the paper, is to "maintain a relatively steady sending rate while still being responsive to congestion" [8]. It accomplishes this by calculating a threshold sending rate using a sophisticated response function. If the actual sending rate is below this threshold, the sender can increase its sending rate. Whenever the actual sending rate goes above this threshold, the sender must decrease the sending rate to the threshold value. These increases and decreases should be gradual to prevent a "burst" of packets into the network or a sudden drop in the sending rate.

2.2.2 Router Techniques

Another approach to congestion control and avoidance is to selectively drop packets inside the network, instead of at the entry points. This usually occurs when the volume of traffic in the network exceeds a certain threshold.

Random Early Detection (RED) [4, 9] is a congestion avoidance technique similar to DECbit. First, RED computes an average queue length using a weighted running average. When a packet arrives at a router, it is dropped if the average queue length is greater than a maximum threshold, queued if lesser than a minimum threshold, or dropped with probability P if between the two thresholds. RED provides an equation for calculating *P* as a function of the average queue length. RED with In and Out (RIO) [4] is a form of RED that has two classes of packets, "in" and "out" - the "out" packets have lower thresholds and are likely to be dropped first.

In Fair Queueing, routers keep a queue for each flow passing through them, and service the queues, bit by bit, in round-robin fashion. Weighted Fair Queueing (WFQ) assigns a weight to each queue that specifies how many bits to transmit each time the router serves that queue. Both of these techniques drop packets in a flow if that flow sends more data than the router can hold in its largest allowable queue [4]. Core-Stateless Fair Queueing [10] attempts to approximate Fair Queueing with a much lower complexity in core routers. Edge routers maintain per-flow information, while core routers use that information to determine if a flow is using its fair share of the network. Flows that use more than their fair share begin getting their packets dropped by core routers.

2.2.3 Alternate Methods

This final category of techniques includes all those that do not restrict or drop packets in the network for the purposes of controlling or avoiding congestion. Instead, these techniques use alternate approaches for handling congestion.

Caching involves the storage of network data in a place that will make it retrievable more quickly than if it had to be fetched from the source [4]. It also reduces traffic on the backbones of networks. A recent case study of the MSNBC web site concluded that caching small numbers of heavily accessed documents might reduce the load and Web traffic of the server significantly [11].

Service classes ensure quality of service for every flow and accommodate the needs of a variety of networked applications [4]. Traffic engineers have already applied the service classes concept to freeways in the form of HOV lanes and truck lane restrictions.

2.3 Traffic Flow Control Research

Engineers and others interested in traffic systems have attempted to improve traffic flow and reduce congestion on highways for about as long as traffic congestion has existed. What follows is a sampling of some of these attempts, particularly those that involve ramp metering or highway monitoring.

2.3.1 Herman and Gardels: Platooning in the Holland Tunnel

Herman and Gardels [2] attempted to develop a mathematical model of traffic flow nearly forty years ago, and used their model to alleviate traffic problems in the Holland Tunnel. They called their solution platooning, defined as restricting the number of vehicles entering a roadway (in this case, the roadway through the tunnel) in a given time. They calculated the maximum throughput that the tunnel could achieve, which was 44 vehicles every two minutes. They then used platooning at the entry points of the tunnel to ensure that this throughput was maintained. That is, no more than 44 vehicles were allowed to enter the tunnel every two minutes, to prevent inhibiting traffic flow through the tunnel. They found through extensive statistical measurement that platooning resulted in greater flow through the tunnel, less pollution, and fewer breakdowns. Additionally, it separated groups of vehicles into "platoons" that had little or no effect on one another. These platoons limited the braking "shock waves" that often result from packs of vehicles following one another (following vehicles over-compensate in response to the braking actions of the leading vehicle). Variations of their technique resurfaced many times since then as an effective way to ease traffic congestion.

2.3.2 Bumper to Bumper Report: On-Ramp Entrance Control

A less scientific attempt at reducing traffic congestion was made by the Legislative Commission on Critical Transportation Choices for New York state [1]. This committee did a review of New York's traffic congestion problem, and wrote a report outlining the causes of the problem and some steps taken to mitigate it. Among those steps were the expected responses, such as carpooling incentives, public transit subsidies, and increased highway capacity. However, the committee also recognized the need for solutions that dealt more directly with maximizing traffic flow. These solutions included traffic signal optimization, the INFORM system, and on-ramp entrance control. The INFORM system was intended to reduce congestion by informing motorists of upcoming delays and accidents. This information led to the use of alternate routes by motorists, so that traffic volume was more evenly dispersed among all routes. The on-ramp entrance control was a form of platooning that intended to keep traffic volume from exceeding the capacity of a limited access highway. A computerized system used speed and volume data from electronic sensors to control the timing of entrance signal lights and achieve maximum traffic flow. Overall, the system has been quite a success. According to the New York State Department of Transportation web site, "estimates show ITS Variable

Message signs save 300,000 vehicle hours annually with the original INFORM system" [12].

2.3.3 Manual on Uniform Traffic Control Devices: Ramp Signals

The Federal Highway Administration sets the standard for ramp control signals, which are the signals used to implement a platooning or ramp metering system on a freeway. The Manual on Uniform Traffic Control Devices (MUTCD) [13] outlines some guidelines to consider when implementing a system, but states that the decision to start using such a system, and the timing of the system, need to be the result of an "engineering study" [13]. It does not, however, specify clearly any parameters for implementation and timing.

2.3.4 Sample Study on Real-Time Ramp Metering

The Texas Transportation Institute conducted a study on real-time ramp metering, and tested an extensive system of its own creation [14]. This study is a good example of a system for ramp control signals based on an "engineering study" [13]. The system, known as the Advanced Real-Time Ramp Metering System (ARMS), contained three levels of control algorithms to increase traffic flow on highways: free-flow control, congestion prediction, and congestion resolution. The first level, free-flow control, rapidly adapts ramp-metering controllers to current traffic conditions on the highway. The second level, congestion prediction, recognizes patterns that predict imminent traffic congestion or traffic flow breakdown. Finally, the third level attempts to resolve congestion "in a flexible manner" [14] should the first two levels fail to prevent it. The report on the study describes these algorithms in considerable detail. Since the system is quite complex, I was not surprised when unable to locate an instance of its real-life implementation. However, at least one report has described ARMS as a novel algorithm that stands out as having the potential to perform very well, despite its complexity [15].

2.3.5 Common Ramp Metering Techniques

There are several ramp-metering techniques commonly used in today's freeway systems. These are also the ramp-metering techniques supplied by the FRESIM model, which is part of the CORSIM model and the TSIS 5.0 simulation software [16], which is formally introduced in Section 3.1.

Clock-time metering is the simplest type of ramp metering provided by the software. A headway is provided, which is the time in between green lights (which typically let in only one vehicle per green) on the ramp signal. The inverse of the headway is the metering rate of the on-ramp. This metering rate remains constant regardless of what is happening on the freeway itself.

Demand/Capacity metering evaluates the excess capacity downstream of the on-ramp, and adjusts the metering rate to take advantage of this capacity, but never to exceed it. To evaluate excess capacity downstream, this technique requires a detector that reports data back to the ramp meter to be placed on the freeway.

Speed Control metering also requires a detector, but it instead is placed upstream of the on-ramp. This detector measures the current speed of the freeway and reports it back to the ramp meter. It compares this speed to a table of speed thresholds and headways, and sets the metering signal to the headway associated with the lowest threshold speed that is higher than the measured speed.

Multiple Threshold Occupancy metering works in a way that is similar to speed control metering. A detector is placed upstream of the on-ramp, but instead reports the current occupancy of that segment of the freeway. The occupancy is the percentage of time that the detector senses a vehicle during that time interval. A high occupancy would be indicative of closer following vehicles, and probably slower speeds due to congestion. The measured occupancy is compared to a table of occupancy thresholds and metering rates. As with speed control metering, the metering signal is set to the metering rate associated with the lowest occupancy threshold that is higher than the measured occupancy.

ALINEA is the most mathematically sophisticated technique provided by the FRESIM model. This technique calculates metering rates according to the formula

$$R(i) = R(i-1) + K_R[\hat{O} - O_{out}(i)]$$

where *R(i)* is metering rate for the current interval, *R(i-1)* is the metering rate for the previous interval, K_R is a constant parameter that determines how strongly the technique reacts to a change in occupancy, and $[\hat{O} - O_{out}(i)]$ is the difference between a specified target occupancy and the occupancy measured from the detector. If the measured occupancy is greater than the target occupancy, the metering rate will be decreased, and if the measured occupancy is less than the target occupancy, the metering rate will be increased. This increase or decrease is a function of the magnitude of the difference between the measured and target occupancies.

2.4 Comparison of Data Networks and Freeway Systems

Data networks have much in common with traffic systems. A data network allows for flow of information along limited pathways much in the same way that road networks allow for the flow of traffic. Furthermore, one could see a network packet travelling along a path of nodes as analogous to a vehicle travelling on a roadway. A source employing the Transmission Control Protocol (TCP) [3] and congestion control techniques to send packets of data could be equivalent to an on-ramp using a ramp metering technique to send vehicles onto a freeway. Therefore, it is possible that modifications to the TCP protocol, or another area of the network, that improve flow, capacity, and travel time, will cross-apply themselves to the analogous component of the traffic system (usually highway on-ramps).

In adapting these techniques to traffic systems, equivalents must be found for both the congestion window and the acknowledgements. The freeway on-ramp, with ramp metering, performs essentially the same function as a congestion window in a data network. Both are designed to permit and restrict entry into their respective systems. Acknowledgements seem to have no intuitive equivalent. We would need somehow to catalog the vehicles that enter the freeway and make note of when they exit successfully. Additionally, we need to have a "timeout" for these vehicles that indicates congestion, as all vehicles will eventually acknowledge, or better stated, it is impossible to have a "lost" vehicle in the same sense as a "lost" packet. It is relatively easy to "drop" a packet in a data network, while it is physically impossible to "drop" a vehicle on a freeway.

On the other hand, we may not need to find an equivalent for acknowledgments. A "lost" packet is only used to show that congestion exists, and that a network congestion control technique must resolve it. Freeways, however, have another method of determining congestion - with occupancy measurements from detectors placed on the freeway. These detectors provide a definitive measure of congestion on freeways, and eliminate the need for the assumptions and guesswork typically made by network congestion control techniques. Since a central authority, such as a state Department of Transportation, generally has total control over a traffic network, it can place detectors anywhere it wants and use the measurements anywhere it wants in the system. Large-scale data networks are decentralized and cross many administrative domains, making such close monitoring considerably harder, and requiring the additional guesswork. This difference, in a sense, makes congestion control and avoidance easier in traffic networks than in data networks.

These differences make cross-application considerably more difficult than it looks on the surface. For example, since detectors all but eliminate the guesswork required of network congestion control techniques, each technique's application to the freeway on-ramps will take a considerably more predetermined form. This form will usually be a multiple threshold occupancy meter at the on-ramp.

Additionally, certain network congestion control techniques have a tendency to drop the sending rate dramatically when there is heavy congestion in the network. This is generally not a serious problem in data networks - the client simply waits or tries again later. While the client might find this frustrating, such a situation at a freeway on-ramp would likely lead to irate drivers, as the freeway congestion might not resolve for several hours, leaving the driver stranded at the on-ramp. The driver has no option to try again later, especially if there is no "escape" from the line of vehicles waiting to enter the freeway. Techniques that produce such unreasonably long wait times must be avoided.

To understand further the similarities and differences between data and traffic networks, it should be beneficial to define three general network performance measurements for both systems. These measurements are throughput, average latency, and latency variability.

Throughput in traffic networks is the number of vehicles that can travel over a segment of a road in a given time period. The definition of throughput for data networks is similar: the number of bits that can be transmitted over a network in a given time period. Average latency in traffic networks is the average travel time of vehicles using a segment of the road. Similarly, in data networks this is the average time it takes for a data message to travel from one end of a network to the other. Latency variability in traffic networks is the variation in travel time of individual vehicles using a segment of a road. In data networks, this is also known as jitter, and is defined as variation in network latency between blocks of data [4].

The limiting factor in data networks is often throughput, while in traffic networks the limiting factor is generally latency. Latency in data networks is often less of an issue, and sometimes negligible. The reverse is true for traffic engineers - throughput is important, but a latency improvement is more significant than one that squeezes a few more vehicles onto the road. Latency variability is often a cause for concern in data networks, especially those that use streaming audio or video applications [4], and is equally unacceptable in traffic networks, except in special cases such as HOV lanes.

3. SIMULATING THE TRAFFIC SYSTEM

3.1 CORSIM

TSIS 5.0 is the software package that was used to create the simulation. TSIS 5.0 [16] is a graphical overlay for CORSIM, a widely used traffic simulator that is the product of thirty years of research on traffic behavior by the Federal Highway Administration. CORSIM combines two powerful simulation tools: FRESIM for freeways and NETSIM for surface streets. It simulates a traffic system at the level of individual vehicles, accounting for their movements and interactions with other vehicles, traffic control devices, signs and signals, and the road itself [17]. In terms of performance, CORSIM is a highly complex simulation tool that does a satisfactory job of simulating roadways with congestion when fine-tuned enough, and a much better job of simulating roadways without congestion.

3.2 Freeway Model

The first steps in creating this simulation involved choosing a suitable freeway and then collecting the necessary information to simulate it. The freeway chosen was Interstate 66 westbound in Northern Virginia. The segment simulated was from the last on-ramp from the Capital Beltway (Interstate 495) through the Route 28 interchange, a distance of approximately eleven to twelve miles. Figure 3.1 shows the simulated area of Interstate 66.

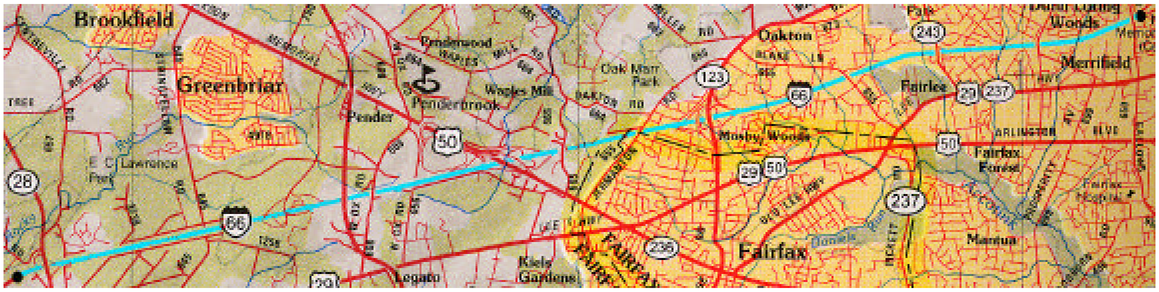

Figure 3.1 - Simulated Segment of Interstate 66 [18]
(Segment highlighted in blue)

Interstate 66 was chosen because it is a heavily congested freeway corridor, representative of many of the roads in the Northern Virginia area during rush hour. The segment chosen is relatively uniform in design, with three regular lanes and one HOV lane during peak-hour traffic. It is also the most congested segment of the freeway westbound (or outside) of the Capital Beltway. Both the simulation data and the raw data collected from the freeway confirm this. I chose the westbound direction over the eastbound because it was the direction for which peak-hour data was available.

A Northern Virginia roadmap from ADC [5] provided most of the structural information about the road, such as distances between entrances and exits and a general idea of the layout of Interstate 66. The Smart Travel Lab provided the volume information needed to populate and validate the system. This data also provided more information about the structure of the road, such as lane counts and layout information. When neither of these two sources could answer a question about the freeway, road maps or aerial photographs available on the web from MapQuest [6] provided the additional information.

Hundreds of detectors placed throughout Interstate 66 supplied the volume data provided by the Smart Travel Lab. The specific data used to populate the simulation was collected from detectors between 6 and 7 p.m. on February 21, 2002. Volumes were provided for the freeway itself and numerous off-ramps and on-ramps. The data was not 100% comprehensive, however, and therefore volume estimates had to be made for one segment of the freeway in the Route 50 interchange, a lane of the freeway in the Route 123 interchange, the off-ramp for Route 28 northbound, and the HOV off-ramp for Monument Drive. Since none of these values was needed as entry node data for the freeway simulation, however, these data holes were only an issue in the validation of the simulation, and not an issue in its creation.

3.3 Simulating Interstate 66

Once the necessary information was collected and organized, the simulation was created in TSIS 5.0 [16]. I created the infrastructure first and then populated it with the volume information. TSIS 5.0 required on-ramp and freeway entry data to be provided as a vehicles per hour flow, but off-ramp data needed to be provided as a percentage of total flow through that segment of the freeway. This becomes important during the validation process, since any deviation of simulated volumes from actual volumes in a segment of the freeway would create proportional deviations from actual volumes at the off-ramps. This, in turn, would magnify and propagate these inaccuracies to further segments of the freeway.

I obtained defaults from the Highway Capacity Manual [19] for some information that was not provided by any source. These defaults included acceleration lanes of 600 feet, deceleration lanes of 150 ft, and a relative volume of 5% trucks and heavy vehicles. An approximate percentage of 10% was calculated from the Smart Travel Lab data for the relative number of high occupancy vehicles (those that could use HOV lanes) on the road at any given time. Lastly, I gave drivers an average free-flow speed of 65 mph, and a range of free-flow speeds between approximately 55 and 75 mph. Although the speed limit on this segment of Interstate 66 is 55 mph, data from the Smart Travel Lab and personal experience on the road showed a range of speeds closer to that used in the simulation.

The simulation was validated by comparing hourly vehicle volumes generated by the simulation to the actual hourly volumes from the Smart Travel Lab data. I compared simulation and actual data from the on-ramps, off-ramps, and freeway segments. Overall, the simulation volumes were relatively consistent with the data provided from the Smart Travel Lab. Figure 3.2 compares the simulation and actual vehicle volumes for all freeway segments for which reasonably complete data was available. Refer to Appendix A for a numerical comparison of actual and simulation volumes, including on-ramp and off-ramp volumes accompanied by additional freeway data.

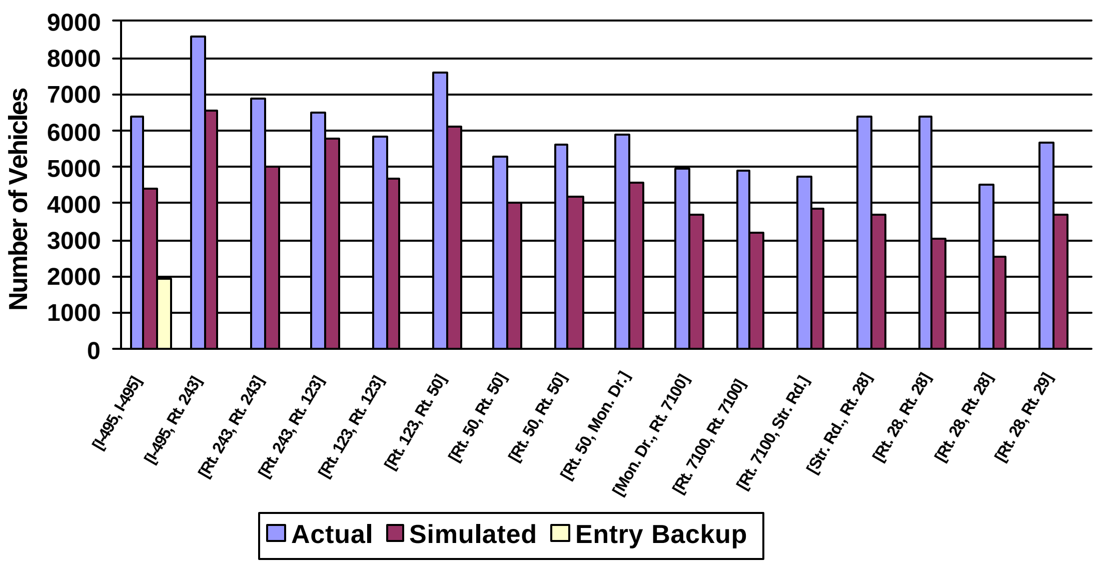

Figure 3.2 - Comparison of Simulated and Actual Vehicle Volumes
(Freeway segments shown in order as [Prev. Route, Next Route] pairs)

The largest problems occurred because of vehicle backup behind the entry points of the simulation. Approximately 2,400 vehicles programmed to enter the simulation during the hour never made it into the freeway from the freeway entry point (hence the entry backup on the first freeway segment shown in Figure 3.2) and several on-ramps near the beginning of the simulated roadway segment. This number was originally higher but alleviated with extensive manipulation of simulation parameters, including use of the default information described earlier. This created queues of vehicles at some entry points that were waiting to enter the freeway due to a lack of physical road space. This failure of 2,400 vehicles to enter the freeway prevented accurate flow readouts from many areas of the freeway and off-ramps. Later in the simulation, the on-ramp data are more accurate, since zero vehicles backed up behind the on-ramp entry points. However, the freeway data are about 1,500 to 2,000 vehicles fewer than it should be in all areas, due to the congestion issues at the beginning of the simulation. Additionally, the off-ramp readings are somewhat lower, due to the need to provide off-ramp data as a percentage of total flow through a segment of the freeway, as mentioned earlier.

One reason for these vehicle backups behind the entry points probably has to do with the aggressiveness level of drivers in the simulation. It is likely that the actual drivers on Interstate 66 are considerably more aggressive with both road entry maneuvers and following distances. The CORSIM simulator places vehicles with a number of different driving behaviors on the road - a driver has the same chance of being overly cautious as overly aggressive. After an exhaustive search of the program, it is my conclusion, unfortunately, that the frequency of aggressive drivers cannot be adjusted in the CORSIM model, and I was therefore forced to keep this bell curve distribution of driving behaviors. In contrast, Interstate 66 has considerably more aggressive drivers than careful ones, based on my personal experience driving the road, meaning closer following distances and more aggressive actions to enter the freeway. These two factors would lead to increased freeway volume and greater congestion.

Additionally, CORSIM tends to project a pessimistic view of driver behavior when it comes to lane changes. CORSIM drivers do not like to let vehicles into their lane if their following distance will be violated. In real life, violation of a driver's following distance is usually the only way to enter the freeway in such a congestion situation. This could therefore be partially responsible for the large queues of waiting vehicles.

Regardless of these flaws, however, I chose to use this simulation to perform the experiments, as it still does a reasonably good job of representing this freeway. Furthermore, it still models a very realistic freeway scenario, which is what is most important for the purposes of these experiments. This simulation gave me the control data that I needed to make comparisons. The control data are better to use for comparisons than the actual data, as all of it was obtained in the same environment from which the experimental data was obtained. This allows one to see clearly the effects of the experiments that were performed. Additionally, the actual data contains a significant amount of measurement error that would skew any conclusions that one attempted to draw from comparison after completion of the experiments.

4. EXPERIMENTATION

4.1 Applying Each Technique

I applied each technique to the traffic system and then compared it to the control data in a number of different areas, including calculated on-ramp wait times and total travel time through the freeway segment. The data included volumes at specific parts of the freeway, including on-ramps and off-ramps, travel times through freeway segments, and backups of vehicles behind entry points and on-ramps in the simulation. Although measuring the flow directly does not tell us much, we indirectly get a sense of the number of vehicles that the freeway services during the simulated hour of operation through the numbers of vehicles queued behind the entry points. For example, the simulation without any congestion control techniques allowed 12,438 vehicles to enter out of 14,838 wanting to use the freeway during that hour, about an 84% service rate.

Most of the techniques applied to the simulation were modified to be considerably more predictable and predetermined than they usually are in data networks. I did this for reasons discussed in the section comparing data networks and traffic systems, and because the simulation software required each technique to be pigeon-holed into one of five ramp metering techniques. Consequently, I used a multiple threshold occupancy meter, calibrated with the philosophy of the congestion control scheme in mind, to apply most of the techniques.

Additionally, techniques that used multiple threshold occupancy metering only metered three of the on-ramps in the simulation - the rest remained unmetered. The primary reason for this was that the simulation software had internal problems with implementing more than about three multiple threshold occupancy on-ramp meters.

Practically, however, this was enough, since traffic-slowing congestion only occurred in the first segments of the simulation, where these on-ramp meters were placed. Since the later segments approached free-flow speed, it made no sense to meter downstream on-ramps. Such metering would cause queue buildup at those on-ramps with no added benefit.

Table 4.1 lists the descriptions of the implementation algorithms for applying each of the techniques to the simulation, with more detailed information available in Appendix B.

Congestion Control Algorithm	Algorithm Description
Ethernet	Applied 1-persistence congestion control with no exponential back-off. Metered at maximum rate if no congestion, else minimum rate. Used Multiple Threshold Occupancy Meter.
AIMD	Allowed one extra vehicle per minute as congestion lessened. During congestion, metering rate was halved as congestion got worse. Used Multiple Threshold Occupancy Meter.
Slow-Start	Doubled metering rate when congestion lessened, halved when congestion worsened. Prevented "burst" with an even metering rate for low and moderate congestion levels. (Simple implementation.) Used Multiple Threshold Occupancy Meter.
TCP Vegas	Defined occupancy thresholds for too little and too much traffic on the freeway, increased ramp-metering rate below minimum threshold, and decreased it above maximum threshold. Used Multiple Threshold Occupancy Meter.
DECbit	Decreased metering rate by one-eighth as congestion worsened. Used Multiple Threshold Occupancy Meter.
Friendly Rate Control	Increased metering a little as congestion lightened; dropped to threshold value when congestion increased, and held that rate even if congestion got worse. Never reacted harshly to excess capacity/congestion. Used Multiple Threshold Occupancy Meter.
RED	Metered at maximum rate if no congestion, else lowered rate as congestion got worse, and metered at minimum rate at a certain threshold. Used Multiple Threshold Occupancy Meter.
Fair Queueing/WFQ	Metered all on-ramps at the same rate ("fairly"). Weighted metering applied for a WFQ system, to allow proportionally more vehicles from on-ramps that were more popular. Used clock-time metering.
Lane Added	Added an additional lane to this segment of Interstate 66 to increase the capacity on the freeway where it was needed most.

Table 4.1 - Procedures for Applying Congestion Control Techniques

As an example of how I cross-applied techniques, and to help with understanding the table, we can consider the implementation algorithm for DECbit. DECbit was described earlier as a technique that marked packets to determine congestion, and decreased the sending rate by one-eighth while congestion persisted, or increased the rate linearly when below a certain congestion threshold. In applying this technique to the freeway system, I chose to use a multiple threshold occupancy meter. Since the detectors in the roadway could give us a much better idea of how much congestion existed than the estimation used in the real DECbit algorithm, I chose to adapt the technique to the detector information. The resulting implementation algorithm was considerably more deterministic than the real DECbit congestion control scheme, as was the case with every technique modified for the simulation. Rather than decreasing the metering rate by one-eighth while congestion persisted, I decided to decrease the metering rate as congestion got progressively worse, as defined by a number of occupancy thresholds. The baseline for the technique was the maximum metering rate (15 vehicles/minute/on-ramp lane) and zero percent occupancy. Whenever congestion worsened and exceeded an occupancy threshold, the current metering rate decreased by one-eighth. There was no linear increase for congestion resolution, but the metering rate was allowed to increase again when congestion dropped below a threshold.

4.2 Experimental Results

The results show us almost immediately that some congestion control techniques fail miserably at their task, generally because of tremendously unreasonable on-ramp wait times. As was hinted earlier, the techniques that dramatically reduce flow in response to congestion were some of the worst to fare in the experiment, producing on-ramp wait times of up to, in the most extreme case, fifteen hours. Deploying such techniques would likely lead to a level of road rage far worse than any benefits produced from improved travel times or throughput. The following figures summarize the results of the experiment. Figure 4.1 shows travel time for the entire freeway segment, not including on-ramp wait or entry times, for each congestion control technique. Figure 4.2 shows throughput for the techniques, measured in number of vehicles that were able to enter the freeway at that hour. Finally, Figure 4.3 gives us the average on-ramp wait times of all metered on-ramps for each technique. All techniques are compared to the control simulation and free-flow conditions. Free-flow means that vehicles always travel the freeway at 65 mph, with nothing impeding their speed, and that all vehicles wanting to enter the freeway are allowed to do so immediately. In other words, free-flow indicates a freeway with infinite traffic capacity and no delay time. Appendices C and D contain further results from these experiments.

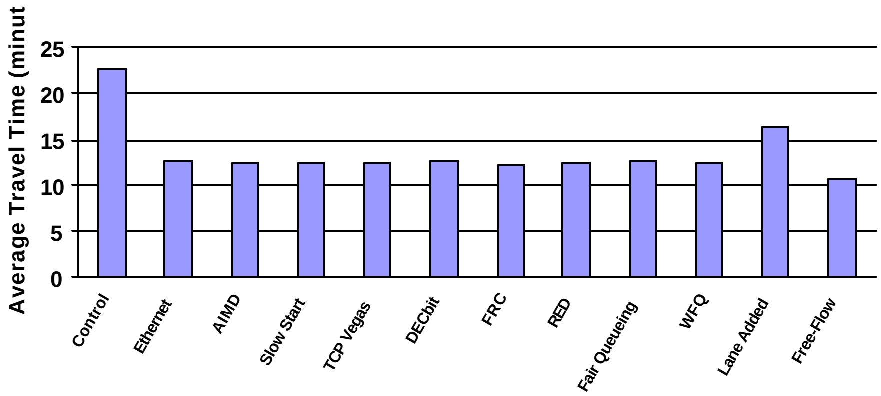

Figure 4.1 - Freeway Travel Times for Each Technique

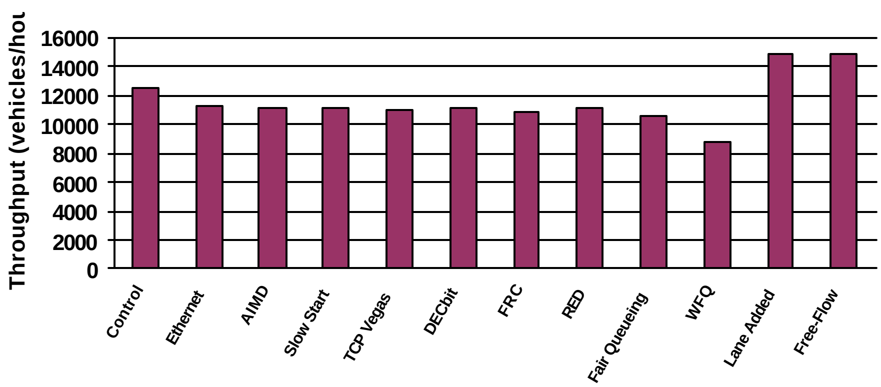

Figure 4.2 - Throughput for Each Technique

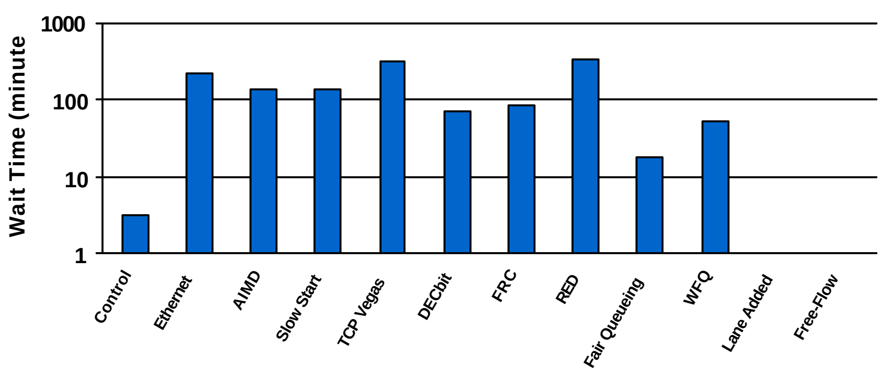

Figure 4.3 - Average On-Ramp Wait Times for Each Technique
(Lane Added & Free-Flow Wait Times were less than one minute)

A successful technique achieves a balance between travel time, throughput, and on-ramp waiting times. Many techniques, such as Ethernet, AIMD, and RED, achieved good travel times, but their on-ramp waiting times were very high. Other techniques, such as Weighted Fair Queueing, did an okay job of balancing on-ramp wait times and travel times, but at the expense of a considerably decreased throughput. All of the ramp metering techniques had a decrease in throughput from the control, since they alleviated congestion on the freeway by moderating vehicle entry at on-ramps, thereby allowing fewer vehicles to use the freeway during the hour.

Overall, it would appear that none of the simulation techniques performed tremendously well except for adding a lane, which had a significant improvement in all areas. Unfortunately, all that really shows is that adding a lane to a freeway improves flow, capacity, and travel times, which is not an interesting or particularly relevant conclusion for this project. Adding a lane, however, does reduce congestion to a level at which the techniques may become more useful. The techniques that appear to have the most promising results, if fine-tuned and applied alongside the addition of an extra freeway lane, are DECbit, Friendly Rate Control, and Fair Queueing. The combination and fine-tuning of techniques to achieve maximum positive effects are the focus of the next chapter.

5. PRAGMATIC TECHNIQUE APPLICATION

5.1 Combining and Fine-tuning Successful Techniques

The results indicated that adding a lane to the freeway simulation increased the capacity of the road, provided lower travel times and entry wait times, and increased throughput. This chapter will demonstrate the ability of DECbit and fine-tuned versions of Fair Queueing and Friendly Rate Control, combined with the addition of a lane to the freeway, to have a considerable effect on freeway performance. Adding a lane reduces congestion and increases the success of the techniques, as most techniques were unsuccessful where the traffic network was overloaded. Often, combining the addition of a lane with these techniques improved travel times and throughputs while cutting average on-ramp waiting times by as much as half. The techniques were generally fine-tuned by increasing their average metering rates in order to take advantage of the newly available lane capacity.

As a series of follow up experiments, the addition of a lane was first combined with the DECbit technique. DECbit was unmodified before combination, as any modification would either reduce the metering rates or compromise the accurate emulation of the DECbit algorithm. The next experiment was to combine the addition of a lane with a fine-tuned version of Friendly Rate Control with a slightly higher average metering rate. Next, Friendly Rate Control was fine-tuned even further to supply the highest average metering rate possible while still emulating the algorithm accurately. Finally, Fair Queueing was implemented on the three on-ramps to which most of the congestion control techniques were exclusively applied. This would eliminate the issue of queue buildup on areas of the freeway where metering did not provide any noticeable benefits. Additionally, the metering rate was increased to the maximum rate possible (15 vehicles per minute), again to maximize use of freeway capacity. Lastly, this technique was also combined with the addition of a lane to the freeway. Appendix B contains more information on these follow-up experiments.

The following figures summarize the results of these experiments and compare the effectiveness of the combinations with their separate application. Figure 5.1 shows travel time for the entire freeway segment, not including on-ramp wait or entry times, for each set of techniques. Figure 5.2 shows throughput for each set of techniques, measured in number of vehicles that were able to enter the freeway at that hour. Finally, Figure 5.3 gives us the average on-ramp wait times of all metered on-ramps for each set of techniques. All sets of techniques are compared to the control simulation and free-flow conditions. Appendices C and D contain further results from these experiments.

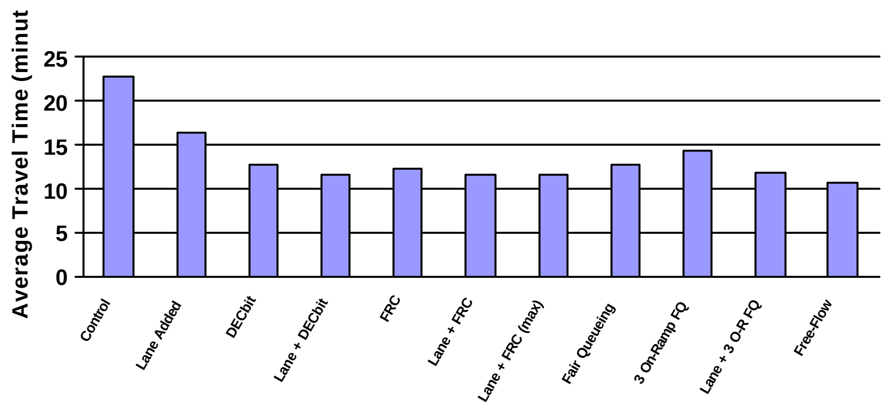

Figure 5.1 - Freeway Travel Times for Combinations of Techniques

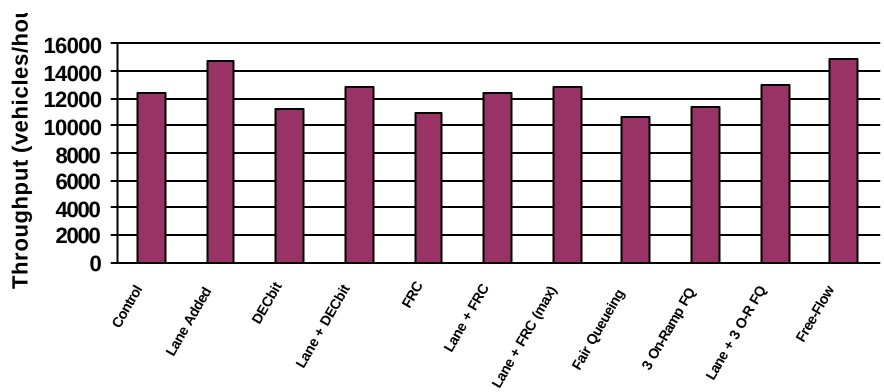

Figure 5.2 - Throughput for Combinations of Techniques

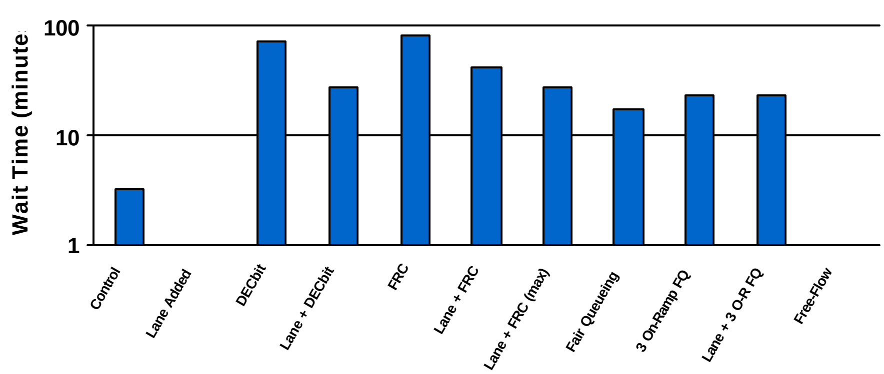

Figure 5.3 - Average On-Ramp Wait Times for Combinations of Techniques (Lane Added & Free-Flow Wait Times were less than one minute)

One could conclude from the figures that these improved techniques on a less overloaded freeway were superior to their earlier application. Overall, it appears that maximum rate Fair Queueing combined with the addition of a lane was most successful at achieving a balance between travel time, throughput, and on-ramp waiting times. DECbit and maximized Friendly Rate Control were close, when given an additional lane, but did not achieve the balance as well. Comparing the three techniques, Fair Queueing had a slightly greater freeway travel time, but a significantly greater throughput of about 200 vehicles, and an average metered on-ramp wait time of about five minutes less.

5.2 Evaluation of Most Successful Combination

Luckily, the most successful combination of techniques is also a rather easy one to apply in real life. Three on-ramp meters would be placed at the final Interstate 495 on-ramp as well as the Nutley Street on-ramp and the second Route 123 on-ramp. These on-ramp meters are simply clock-time ramp meters with a headway of four seconds. The more costly part of this project would be the addition of an extra lane to this segment of Interstate 66. Since Fair Queueing on three on-ramps actually performs reasonably well on its own, however, it is possible to start the metering signals before finishing the road widening project in order to benefit from them as early as possible. This road improvement project would literally cut travel times along this segment in half and increase throughput by approximately 600 vehicles, at the cost of a 20-25 minute wait on three of the entry on-ramps. Such a wait, unfortunately, would not be accepted by the public. The wait time at these on-ramps is simply too long for the drivers to benefit from the improvement in travel times on the actual freeway.

6. CONCLUSIONS

6.1 Summary of Findings

This project measured the ability of data network congestion control techniques, in a simulated freeway environment, to decrease travel time and increase throughput and capacity while avoiding unacceptably long wait times at freeway on-ramps. Despite the differences between vehicular traffic and data networks, this project demonstrated that physical vehicles on a roadway often respond to the same congestion control and avoidance techniques as abstract data packets on a communications line. The results indicate potential for the cross-application of data network congestion control techniques to congested freeways.

A successful technique would achieve the best balance between travel time, throughput, and on-ramp waiting times. Many of the techniques achieved good travel times, but their on-ramp waiting times were very high. Other techniques did a good job of balancing on-ramp wait times and travel times, but at the expense of a considerably decreased throughput. Applied separately, the techniques that appeared most promising for fine-tuning or combination with adding a lane for increased road capacity were DECbit, Friendly Rate Control, and Fair Queueing.

Combinations of those techniques were indeed superior to their separate application. The combination that was most successful at achieving a balance between travel time, throughput, and on-ramp waiting times was maximum rate Fair Queueing combined with the addition of a lane to the freeway. This combination beat out adding a lane to either DECbit or maximized Friendly Rate Control by a slim but significant margin.

One obvious reason that this combination was successful is that adding a lane increases the capacity of the freeway, which automatically lightens congestion and makes most of the other techniques more effective. Furthermore, I mentioned earlier that ramp metering techniques that respond too drastically to an increase or decrease in congestion tend to fare much worse than those that respond more gradually. Clients on a network can be expected to put up with the occasional unreasonable delay - drivers usually cannot. In fact, it appears that in freeway systems, often it is best not to modify the metering rate at all, but instead to program the ramp meter with a constant headway that fully uses available capacity without causing congestion. Certainly, this proved to be the best balancing technique in this sequence of experiments. Perhaps, however, a correctly calibrated adaptive metering technique would prove more effective in another experimental sequence.

6.2 Discussion and Interpretation of Results

The most promising combination to apply to a freeway for the greatest positive net effect is maximized Fair Queueing combined with the addition of a lane to the freeway. This combination would provide a significant decrease in freeway travel time and increase in throughput. However, it would also provide a significant wait at certain on-ramps of nearly 20-25 minutes. This is a 15-20 minute increase from the wait before applying any congestion control techniques. Would such a wait be a problem? This depends on the magnitude of the decrease in freeway travel time, but it is likely that it would not be acceptable to the driving public. Unreasonable on-ramp delays might lead to an ignorance or avoidance of the system, or protests from drivers to shut down the system. These on-ramp delays might additionally lead to increases in fuel waste and pollution, or leave drivers seeking alternate routes through residential neighborhoods, which would only further justify these protests.

To solve this problem, we might consider applying this congestion control combination to a freeway with suitable alternate routes, or even two parallel freeways. This way, drivers would be encouraged to use the less congested of the two freeways, which would eventually lead to a balance between on-ramp wait times and equal sharing of the traffic load by both roads. Such a technique could alternately be applied to a toll road. In this case, a driver could bypass a long wait by paying a toll to enter the freeway, which would be pro-rated for the anticipated wait time, or could wait it out and eventually enter the road for free. Such a system would allow the most desperate people to use the road for a price, while reimbursing the public for any additional congestion and road stress.

It is also possible that this is not a problem that needs to be solved. I mentioned earlier that drivers were generally less aggressive in the simulation, which led to some of the entry queue problems due to cautious drivers not wanting to compromise their following distances to let people into their lane. This problem might be projecting a very pessimistic on-ramp wait time. If the time is actually only 10-15 minutes in real life, then the application of this combination of techniques becomes much more practical, though people would still probably only use Interstate 66 for longer journeys.

Furthermore, these techniques tested on another freeway system might provide the same gains with less of an on-ramp waiting penalty, which would make them beneficial to more drivers with fewer negative consequences. In particular, these techniques might have a greater likelihood of working on a freeway with less congestion. The segment of Interstate 66 that I simulated is located in a heavily congested area of Northern Virginia, which has traffic congestion problems comparable to the New York City and Los Angeles metropolitan areas. It is quite likely that these three regions have the largest traffic congestion problems in the nation. Applying these techniques to a less problematic road might work a lot better.

We must also keep in mind that any action taken to improve the flow of a road will probably lead to increased confidence in that road and therefore a possible resurgence of higher travel times and longer on-ramp waits. This is an unavoidable side effect of trying to improve any roadway, and its resolution is beyond the scope of this project. It should also be noted that this system would do nothing to improve freeways that are congested due to roadway incidents such as accidents. Therefore, if application of these techniques results in higher incident levels on the freeway, this might be a reason for discontinuing their use. In conclusion, Fair Queueing combined with the addition of a lane is the combination recommended for practical application by this report, as it provides numerous benefits to drivers while keeping the added burdens to a minimum.

6.3 Recommendations for Future Research

This project presents numerous opportunities for future research. One could choose a different road to simulate and perform the same experiments on that simulation. It is quite possible that applying these techniques to a less congested road would be much more effective. Alternately, one could choose to apply these techniques to the same segment of I-66 with a different application strategy.

There are also other research possibilities, given the advancements in the fields of traffic engineering and data networks. A newer, more centralized and deterministic congestion control technique that adapts itself better to traffic systems may be invented. Additionally, networks that are or become more centralized, and can use detectors of some sort to provide more definitive measurements of congestion, might benefit from the application of ramp metering techniques, as they would avoid unnecessary guesswork and provide a cleaner solution to congestion resolution for that network. Alternatively, freeway systems that are more decentralized might benefit from applying one of the data network congestion control techniques outlined in this report.

6.4 Report Summary

This project demonstrated the potential for the cross-application of data network congestion control techniques to congested freeways. The techniques that appeared most promising, when applied separately, for fine-tuning or combination were DECbit, Friendly Rate Control, and Fair Queueing. When techniques were combined and fine-tuned, the combination that was most successful at achieving a balance between travel time, throughput, and on-ramp waiting times was Fair Queueing at the most congested on-ramps combined with the addition of a lane to the freeway. Some reasons why this combination was successful were that adding a lane increases the capacity of the freeway, and that ramp metering techniques fare better when they respond less radically to congestion.

While this combination would provide a significant decrease in freeway travel time and increase in throughput, it would also require a significant wait at certain on-ramps of nearly 20-25 minutes. This wait would likely be a problem in a real-world implementation. Some solutions to this wait problem include alternate routes, parallel freeways, and toll roads pro-rated for current wait time. It is also possible that this wait time problem results from a pessimistic simulation tool or unmanageable levels of congestion on this particular freeway.

This project creates several opportunities for additional research, including modifying the technique application strategies or the freeway on which the experiments are performed. Advancements might lead to other possibilities for research, including application of new techniques or more practical cross-applications of techniques.

Ultimately, this paper hopes to encourage the sharing of information between two similar areas of research - data network and freeway system congestion resolution. Such sharing might not only uncover new ways to reduce congestion in both systems, but might also allow both systems to identify and correct their flaws by using the alternate system as a successful model when appropriate.

WORKS CITED

[1] N. Levy, M. Bragman. *Bumper to Bumper: Transportation Systems Management….* New York: The Legislative Commission on Critical Transportation Choices, 1989.

[2] R. Herman, K. Gardels. Vehicular Traffic Flow. *Scientific American*. p. 35-43. December 1963.

[3] Defense Advanced Research Projects Agency. *RFC 793, Transmission Control Protocol: DARPA Internet Program Protocol Specification*, September 1981.

[4] L. Peterson, B. Davie. *Computer Networks: A Systems Approach*. San Diego: The Academic Press, 2000.

[5] ADC The Map People. *Regional Northern Virginia: The Original Street Map Book*. Alexandria, VA: Langenscheidt Publishing Group, 2001.

[6] MapQuest.com, Inc. *MapQuest*, 2002. http://www.mapquest.com.

[7] Jacobson, V., J. Karels. Congestion Avoidance and Control. In *Proceedings of SIGCOMM '88* (Stanford, CA, Aug. 1988), ACM.

[8] S. Floyd, M. Handley, J. Padhye, J. Widmer. Equation-Based Congestion Control for Unicast Applications. In *Proceedings of SIGCOMM '00* (Stockholm, Sweden, July 2000), ACM.

[9] S. Floyd, V. Jacobson. Random Early Detection Gateways for Congestion Avoidance. In *IEEE/ACM Transactions on Networking*, August 1993.

[10] I. Stoica, S. Shenker, H. Zhang. Core-Stateless Fair Queueing: Achieving Approximately Fair Bandwidth Allocations in High Speed Networks. In *Proceedings of SIGCOMM '98* (Vancouver, British Columbia, September 1998), ACM.

[11] V. Padmanabhan, L. Qiu. The Content and Access Dynamics of a Busy Web Site: Findings and Implications. In *Proceedings of SIGCOMM '00* (Stockholm, Sweden, July 2000), ACM.

[12] New York State Department of Transportation. *LI ITS Benefits*, March 2002. http://www.dot.state.ny.us/reg/r10/benefits.html.

[13] U.S. Department of Transportation, Federal Highway Administration. *Manual on Uniform Traffic Control Devices (MUTCD)*, June 2001. http://mutcd.fhwa.dot.gov/kno-millennium_06.14.01.htm. Sections 4H.01 and 4H.02.

[14] J. Liu, J. Kim. *An Advanced Real-Time Ramp Metering System (ARMS): The System Concept*. Research Report (College Station, TX, November 1994), Texas Transportation Institute.

[15] M. Zhang, T. Kim, X. Nie, W. Jim. *Evaluation of On-Ramp Control Algorithms*. Research Report (Davis, CA, September 2001), Institute of Transportation Studies at the University of California, Davis.

[16] FHWA Office of Operations Research, Development, and Technology. *TSIS 5.0*. Washington, D. C.: ITT Industries Inc., Systems Division, 2001.

[17] New York State Department of Transportation. *New York Route 347 CORSIMS Reference Page*, 2000. http://www.ny347.com/CORSIM.htm.

[18] DeLorme. *Virginia Atlas & Gazetteer*. Yarmouth, MA: DeLorme, 2000.

[19] Transportation Research Board, National Research Council. *Highway Capacity Manual (HCM 2000)*. Washington, D. C.: The National Academy of Sciences, 2000.

BIBLIOGRAPHY

ADC The Map People. *Regional Northern Virginia: The Original Street Map Book*. Alexandria, VA: Langenscheidt Publishing Group, 2001.

Breslau, L., E. Knightly, S. Shenker, I. Stoica, H. Zhang. Endpoint Admission Control: Architectural Issues and Performance. In *Proceedings of SIGCOMM '00* (Stockholm, Sweden, July 2000), ACM.

Byers, J., M. Frumin, G. Horn, M. Luby, M. Mitzenmacher, A. Roetter, W. Shaver. FLID-DL: Congestion Control for Layered Multicast. In *Proceedings of NGC '00* (Palo Alto, CA, November 2000), ACM.

Defense Advanced Research Projects Agency. *RFC 793, Transmission Control Protocol: DARPA Internet Program Protocol Specification*, September 1981.

DeLorme. *Virginia Atlas & Gazetteer*. Yarmouth, MA: DeLorme, 2000.

Evans, D. *Programming the Swarm*. Department of Computer Science (Charlottesville, VA, July 2000), University of Virginia.

Feldmann, A., A. Greenberg, C. Lund, N. Reingold, J. Rexford, F. True. Deriving Traffic Methods for Operational IP Networks: Methodology and Experience. In *Proceedings of SIGCOMM '00* (Stockholm, Sweden, July 2000), ACM.

FHWA Office of Operations Research, Development, and Technology. *TSIS 5.0*. Washington, D. C.: ITT Industries Inc., Systems Division, 2001.

Floyd, S., V. Jacobson. Random Early Detection Gateways for Congestion Avoidance. In *IEEE/ACM Transactions on Networking*, August 1993.

Floyd, S., M. Handley, J. Padhye, J. Widmer. Equation-Based Congestion Control for Unicast Applications. In *Proceedings of SIGCOMM '00* (Stockholm, Sweden, July 2000), ACM.

Herman, R., K. Gardels. Vehicular Traffic Flow. *Scientific American*. p. 35-43. December 1963.

Jacobson, V., J. Karels. Congestion Avoidance and Control. In *Proceedings of SIGCOMM '88* (Stanford, CA, Aug. 1988), ACM.

Levy, N., M. Bragman. *Bumper to Bumper: Transportation Systems Management…*. New York: The Legislative Commission on Critical Transportation Choices, 1989.

Liu, J., J. Kim. *An Advanced Real-Time Ramp Metering System (ARMS): The System Concept*. Research Report (College Station, TX, November 1994), Texas Transportation Institute.

MapQuest.com, Inc. *MapQuest*, 2002. http://www.mapquest.com.

New York State Department of Transportation. *LI ITS Benefits*, March 2002. http://www.dot.state.ny.us/reg/r10/benefits.html.

New York State Department of Transportation. *New York Route 347 CORSIMS Reference Page*, 2000. http://www.ny347.com/CORSIM.htm.

Padmanabhan, V., L. Qiu. The Content and Access Dynamics of a Busy Web Site: Findings and Implications. In *Proceedings of SIGCOMM '00* (Stockholm, Sweden, July 2000), ACM.

Peterson, L., B. Davie. *Computer Networks: A Systems Approach*. San Diego: The Academic Press, 2000.

Resnick, M. *Turtles, Termites, and Traffic Jams*. Cambridge: The MIT Press, 2000.

Stoica, I., S. Shenker, H. Zhang. Core-Stateless Fair Queueing: Achieving Approximately Fair Bandwidth Allocations in High Speed Networks. In *Proceedings of SIGCOMM '98* (Vancouver, British Columbia, September 1998), ACM.

Stoica, I., H. Zhang. Providing Guaranteed Services Without Per Flow Management. In *Proceedings of SIGCOMM '99* (Cambridge, MA, August 1999), ACM.

Thorpe, T. *A Physically-Realistic Simulation of Vehicle Traffic Flow*. Computer Science Technical Report (Fort Collins, CO, January 1998), Colorado State University.

Transportation Research Board, National Research Council. *Highway Capacity Manual (HCM 2000)*. Washington, D. C.: The National Academy of Sciences, 2000.

U.S. Department of Transportation, Federal Highway Administration. *Manual on Uniform Traffic Control Devices (MUTCD)*, June 2001. http://mutcd.fhwa.dot.gov/kno-millennium_06.14.01.htm. Sections 4H.01 and 4H.02.

Zhang, M., T. Kim, X. Nie, W. Jim. *Evaluation of On-Ramp Control Algorithms*. Research Report (Davis, CA, September 2001), Institute of Transportation Studies at the University of California, Davis.

APPENDICES

Appendix A: Simulation Verification Data

February 21, 2002: 6PM Actual Data and Simulation Output for Segment of I-66

LnTyp	*PRN*	*NRN*	*TotLn*	*Actual Volume*	*Simul. Volume*	*Entry Backup*	*Simulated Min/Mile*	*Segment Length (ft)*	*Travel Time (min)*	*Actual % Occ.*	
Norm	Rt 28	Rt 29	5	5694	3696		0.97	750	0.14	7.44	Before Rt. 29
On	Rt 28	Rt 28	1	1133	1132	0	0.96			10.62	Onramp from Rt. 28
Norm	Rt 28	Rt 28	4	4529	2571		0.96	568	0.10	7.38	Rt. 28 Interchange
Off	Rt 28	Rt 28	1	984	442		0.96			9.15	Rt. 28 Offramp #2
Norm	Rt 7100	Rt 28	4	6357	3030		0.96	1563	0.28	10.80	Before Rt. 28
Off	Rt 28	Rt 28	1	~1391	562		1.00			---	Rt. 28 Offramp #1
Norm	Rt 7100	Rt 28	4	6401	3678		0.97	7671	1.41	9.69	Before Rt. 28
HovOff	Rt 7100	Rt 7100	1	177	191		0.97			1.33	Stringfellow Rd. Offramp (HOV)
Norm	Rt 7100	Rt 7100	4	4750	3871		0.97	852	0.16	7.78	Rt. 7100 Interchange
On	Rt 7100	Rt 7100	1	727	725	0	0.95			5.40	Onramp from Rt. 7100
Norm	Rt 7100	Rt 7100	4	4904	3207		0.96	5398	0.98	7.53	Rt. 7100 Interchange
Off	Rt 7100	Rt 7100	1	550	422		0.97			5.37	Rt. 7100 Offramp
Norm	Rt 7100	Rt 7100	4	4936	3684		0.97	4688	0.86	8.17	Rt. 7100 Interchange
HovOff	Rt 50	Rt 7100	1	~965	866		0.97			---	Monument Dr. Offramp (HOV)
Norm	Rt 50	Rt 7100	5	5901	4591		0.98	3125	0.58	7.81	Before Rt. 7100
On	Rt 50	Rt 50	1	419	418	0	0.93			5.28	Onramp from Rt. 50 #2
Norm	Rt 50	Rt 50	4	5619	4183		0.98	994	0.18	9.73	Rt. 50 Interchange
Off	Rt 50	Rt 50	1	216	235		0.97			3.05	Rt. 50 Offramp #2
Norm	Rt 50	Rt 50	4	---	4431		0.98	1421	0.26	---	Rt. 50 Interchange
On	Rt 50	Rt 50	1	434	434	0	0.93			4.58	Onramp from Rt. 50 #1
Norm	Rt 50	Rt 50	4	5317	4013		0.97	1989	0.37	8.82	Rt. 50 Interchange
Off	Rt 50	Rt 50	2	2273	1992		0.98			8.90	Rt. 50 Offramp #1
Norm	Rt 123	Rt 50	5	7589	6126		1.34	6819	1.73	13.16	Before Rt. 50
On	Rt 123	Rt 123	1	1173	1171	0	0.96			14.85	Onramp from Rt. 123 #2
Norm	Rt 123	Rt 123	4	4811	5089		4.30	1847	1.50	25.07	Rt. 123 Interchange
On	Rt 123	Rt 123	1	481	480	0	1.14			6.00	Onramp from Rt. 123 #1
Norm	Rt 123	Rt 123	4	5856	4678		4.45	2131	1.80	23.87	Rt. 123 Interchange
Off	Rt 123	Rt 123	2	596	539		1.42			2.07	Rt. 123 Offramp
Norm	Rt 243	Rt 123	4	6512	5773		3.16	6393	3.83	21.21	Before Rt. 123
On	Rt 243	Rt 243	1	1555	1404	100	3.07			45.82	Onramp from Rt. 243
Norm	Rt 243	Rt 243	4	6870	5003		3.56	7387	4.98	18.52	Rt. 243 Interchange
Off	Rt 243	Rt 243	1	1702	1221		1.18			10.10	Rt. 243 Offramp
Norm	Int 495	Rt 243	4	8570	6550		2.24	7529	3.19	10.06	Before Rt. 243
On	Int 495	Int 495	2	2526	2171	350	8.11			6.53	Onramp from I-495
Norm	Int 495	Int 495	4	6390	4416	1950	7.57	300	0.43	7.70	I-495 Interchange

LnTyp = Lane Type, *PRN* = Previous Route Number, *NRN* = Next Route Number
TotLn = Total Lanes, *Actual % Occ.* = Actual Percent Occupancy

Table A.1 - Simulation Verification Data

Appendix B: Detailed Technique Application Procedures

Congestion Control Algorithm	Algorithm Description MTO Meter Settings Shown as [Metering Rate]([Occupancy Threshold]) Sets
Ethernet	Applied 1-persistence congestion control with no exponential back-off. Metered at maximum rate if no congestion, else minimum rate. Used Multiple Threshold Occupancy Meter: 15(22%), 1(100%). Turned off meter during off-peak times.
AIMD	Allowed one extra vehicle per minute as congestion lessened. During congestion, metering rate was halved as congestion got worse. Used Multiple Threshold Occupancy Meter: 15(5%), 14(10%), 13(15%), 12(22%), 6(35%), 3(100%). Turned off meter during off-peak times.
Slow-Start	Doubled metering rate when congestion lessened, halved when congestion worsened. Prevented "burst" with an even metering rate for low and moderate congestion levels. (Simple implementation.) Used Multiple Threshold Occupancy Meter: 12(22%), 6(35%), 3(100%). Turned off meter during off-peak times.
TCP Vegas	Defined occupancy thresholds for too little and too much traffic on the freeway, increased ramp-metering rate below minimum threshold, and decreased it above maximum threshold. Used Multiple Threshold Occupancy Meter: 15(15%), 8(35%), 1(100%). Turned off meter during off-peak times.
DECbit	Decreased metering rate by one-eighth as congestion worsened. Used Multiple Threshold Occupancy Meter. 15(15%), 13(20%), 11(25%), 9(30%), 7(35%), 6(100%). Not modified when an additional lane added. Turned off meter during off-peak times.
Friendly Rate Control	Increased metering a little as congestion lightened; dropped to threshold value when congestion increased, and held that rate even if congestion got worse. Never reacted harshly to excess capacity/congestion. Used Multiple Threshold Occupancy Meter. 10(10%), 9(15%), 8(22%), 7(100%) 12(10%), 11(15%), 10(22%), 9(100%) [Combined with Added Lane] 15(10%), 14(15%), 13(22%), 12(100%) [Max. + Comb. w/ Added Lane] Turned off meter during off-peak times.
RED	Metered at maximum rate if no congestion, else lowered rate as congestion got worse, and metered at minimum rate at a certain threshold. Used Multiple Threshold Occupancy Meter. 15(15%), 11(20%), 8(25%), 4(30%), 1(100%) Turned off meter during off-peak times.
Fair Queueing/WFQ	Metered all on-ramps at the same rate ("fairly"). Weighted metering applied for a WFQ system, to allow proportionally more vehicles from on-ramps that were more popular. Used clock-time metering: 5 veh/min, 15 veh/min when used on only three on-ramps (even when lane added). Turned off meter during off-peak times.
Lane Added	Added an additional lane to this segment of Interstate 66 to increase the capacity on the freeway where it was needed most. Did not change anything during off-peak times.
Occupancy Readout Interpretation of Congestion: >15%: Moderate, >22%: Heavy, >35%: Stop &Go.	

Table B.1 - Detailed Technique Application Procedures

Appendix C: Experimental Data Summary

Data Summary

Technique	*Average Speed*	*Freeway Trvl. Time*	*Travel Time Red.*	*% Delay Time*	*Total Backup*	*O-R Only*	*Disp. Traffic*	*% Simul. "Let In"*	*Through-put*
Control	30.62	22.79	0.00%	52.87%	2400	450	1950	83.83%	12438
Ethernet	55.38	12.60	44.71%	14.76%	3600	3600	0	75.74%	11238
AIMD	55.96	12.47	45.28%	13.87%	3650	3450	200	75.40%	11188
Slow Start	55.65	12.54	44.98%	14.35%	3750	3500	250	74.73%	11088
TCP Vegas	56.23	12.41	45.55%	13.46%	3850	3850	0	74.05%	10988
DECbit	54.77	12.74	44.10%	15.70%	3650	3050	600	75.40%	11188
FRC	56.64	12.32	45.94%	12.82%	3950	3350	600	73.38%	10888
RED	55.96	12.47	45.28%	13.87%	3700	3700	0	75.06%	11138
FQ	55.12	12.66	44.45%	15.17%	4200	2800	1400	71.69%	10638
WFQ	55.73	12.52	45.06%	14.22%	6100	4400	1700	58.89%	8738
Lane Added	42.42	16.45	27.82%	34.71%	50	50	0	99.66%	14788
Lane + FRC	60.16	11.60	49.10%	7.41%	2500	2500	0	83.15%	12338
Lane + FRC (max)	59.79	11.67	48.79%	7.97%	2000	2000	0	86.52%	12838
Lane + DECbit	59.79	11.67	48.79%	7.97%	2000	2000	0	86.52%	12838
3 Ramp FQ	48.87	14.28	37.34%	24.79%	3500	1800	1700	76.41%	11338
Lane + 3R FQ	59.39	11.75	48.44%	8.60%	1800	1800	0	87.87%	13038
Free-flow	*65.00*	*10.74*	*52.87%*	*0.00%*	*0*	*0*	*0*	*100.00%*	*14838*
Additional Information: 14838 vehicles attempted to enter freeway in the hour, freeway length = 11.63 miles.									

Average Speed in miles per hour, *Freeway Trvl. Time* = Freeway Travel Time in minutes,
Travel Time Red. = Travel Time Reduction from Control,
% Delay Time = Percentage of time above time necessary to travel segment at free-flow,
Total Backup = Total backup behind entry points in vehicles,
O-R Only = Backup behind on-ramp entry points only (excluding freeway entry point),
Disp. Traffic = Backup behind freeway entry point ("displaced traffic")
% Simul. "Let In" = Percentage of traffic allowed to enter freeway that requested to do so

Table C.1 - Experimental Data Summary

Appendix D: Experimental On-Ramp Data

Control	*Ether-net*	*AIMD*	*Slow St.*	*Vegas*	*DECbi*	*FRC*	*RED*	*FQ*	*WFQ*	*Lane Added*	*L + WFQ*	*L + FRC*	*L + FRCm*	*L + DECbit*	*3RFQ*	*L + 3RFQ*	
1132	1132	1132	1132	1132	1132	1132	1132	701	410	1132	403	1132	1132	1132	1132	1132	Rt. 28
725	725	725	725	725	725	725	725	704	261	725	271	725	725	725	725	725	Rt. 7100
418	418	418	418	418	418	418	418	418	157	418	156	418	418	418	418	418	Rt. 50 #2
434	434	434	434	434	434	434	434	433	168	434	164	434	434	434	434	434	Rt. 50 #1
1171	447	529	530	508	532	490	477	697	457	1171	451	652	763	763	859	846	Rt. 123 #2
480	480	480	480	480	480	480	480	480	179	480	178	480	480	480	480	480	Rt. 123 #1
1404	871	713	722	614	779	495	777	693	585	1518	573	699	823	823	853	850	Rt. 243
2171	253	426	417	183	777	862	183	1387	1711	2471	1736	1339	1588	1588	1683	1723	I-495

Table D.1 - Simulated Vehicle Volumes

Control	*Ether-net*	*AIMD*	*Slow St.*	*Vegas*	*DECbi*	*FRC*	*RED*	*FQ*	*WFQ*	*Lane Added*	*L + WFQ*	*L + FRC*	*L + FRCm*	*L + DECbit*	*3RFQ*	*L + 3RFQ*	
0	0	0	0	0	0	0	0	400	700	0	700	0	0	0	0	0	Rt. 28
0	0	0	0	0	0	0	0	0	450	0	450	0	0	0	0	0	Rt. 7100
0	0	0	0	0	0	0	0	0	250	0	250	0	0	0	0	0	Rt. 50 #2
0	0	0	0	0	0	0	0	0	250	0	250	0	0	0	0	0	Rt. 50 #1
0	700	600	600	650	600	650	650	450	700	0	700	500	400	400	300	300	Rt. 123 #2
0	0	0	0	0	0	0	0	0	300	0	300	0	0	0	0	0	Rt. 123 #1
100	650	800	800	900	750	1050	750	850	950	0	950	850	700	700	700	700	Rt. 243
350	2250	2050	2100	2300	1700	1650	2300	1100	800	50	750	1150	900	900	800	800	I-495

Table D.2 - Simulated Approximate Queued Vehicle Counts

Control	*Ether-net*	*AIMD*	*Slow St.*	*Vegas*	*DECbi*	*FRC*	*RED*	*FQ*	*WFQ*	*Lane Added*	*L + WFQ*	*L + FRC*	*L + FRCm*	*L + DECbit*	*3RFQ*	*L + 3RFQ*	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.14	1.99	0.00	1.99	0.00	0.00	0.00	0.00	0.00	Rt. 28
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.28	0.00	1.28	0.00	0.00	0.00	0.00	0.00	Rt. 7100
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.71	0.00	0.71	0.00	0.00	0.00	0.00	0.00	Rt. 50 #2
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.71	0.00	0.71	0.00	0.00	0.00	0.00	0.00	Rt. 50 #1
0.00	1.99	1.70	1.70	1.85	1.70	1.85	1.85	1.28	1.99	0.00	1.99	1.42	1.14	1.14	0.85	0.85	Rt. 123 #2
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.85	0.00	0.85	0.00	0.00	0.00	0.00	0.00	Rt. 123 #1
0.28	1.85	2.27	2.27	2.56	2.13	2.98	2.13	2.41	2.70	0.00	2.70	2.41	1.99	1.99	1.99	1.99	Rt. 243
0.99	6.39	5.82	5.97	6.53	4.83	4.69	6.53	3.13	2.27	0.14	2.13	3.27	2.56	2.56	2.27	2.27	I-495

Table D.3 - Simulated Approximate Queue Lengths (one vehicle = 15 feet, Lengths in Miles)

Control	*Ether-net*	*AIMD*	*Slow St.*	*Vegas*	*DECbi*	*FRC*	*RED*	*FQ*	*WFQ*	*Lane Added*	*L + WFQ*	*L + FRC*	*L + FRCm*	*L + DECbit*	*3RFQ*	*L + 3RFQ*	
0.96	0.96	0.95	0.95	0.96	0.95	0.96	0.96	16.49	28.06	0.95	28.91	0.96	0.96	0.96	0.95	0.96	Rt. 28
0.95	0.94	0.95	0.95	0.94	0.94	0.95	0.95	13.94	46.16	0.95	42.77	0.95	0.95	0.95	0.94	0.95	Rt. 7100
0.93	0.93	0.93	0.93	0.93	0.92	0.92	0.93	3.51	75.36	0.93	72.82	0.92	0.93	0.93	0.93	0.92	Rt. 50 #2
0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	3.52	67.90	0.93	69.75	0.92	0.93	0.93	0.93	0.93	Rt. 50 #1
0.96	24.63	22.53	21.67	23.56	22.00	24.45	24.05	17.08	26.83	0.95	26.49	17.79	14.99	14.99	13.20	13.24	Rt. 123 #2
1.14	1.00	0.94	0.93	0.93	0.94	0.93	0.95	3.52	66.20	1.11	64.74	0.94	0.93	0.93	1.10	0.92	Rt. 123 #1
3.07	12.72	16.54	16.36	19.23	14.83	23.74	14.85	16.97	20.39	1.72	20.20	16.61	13.81	13.81	13.20	13.13	Rt. 243
8.11	93.10	55.04	55.36	128.72	30.27	27.92	138.42	17.08	13.12	3.23	12.77	17.39	14.57	14.57	13.21	12.94	I-495
7.57	*3.19*	*3.97*	*4.17*	*3.40*	*4.53*	*4.61*	*3.70*	*6.17*	*6.92*	*2.26*	*1.09*	*1.04*	1.06	1.06	6.89	1.11	*Pre-Sim Freeway*

Table D.4 - Simulated Approximate On-Ramp Speed (Min/Mile)

Control	Ether-net	AIMD	Slow St.	Vegas	DECbi	FRC	RED	FQ	WFQ	Lane Added	L + WFQ	L + FRC	L + FRCm	L + DECbit	3RFQ	L + 3RFQ	
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	19.68	57.40	0.05	59.13	0.05	0.05	0.05	0.05	0.05	Rt. 28
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.79	61.63	0.05	57.11	0.05	0.05	0.05	0.05	0.05	Rt. 7100
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.20	57.80	0.05	55.86	0.05	0.05	0.05	0.05	0.05	Rt. 50 #2
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.20	52.08	0.05	53.50	0.05	0.05	0.05	0.05	0.05	Rt. 50 #1
0.05	50.38	39.68	38.17	44.84	38.75	46.54	45.78	22.81	54.88	0.05	54.18	26.28	17.89	17.89	12.00	12.04	Rt. 123 #2
0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.20	60.18	0.06	58.85	0.05	0.05	0.05	0.06	0.05	Rt. 123 #1
1.05	24.21	38.53	38.11	50.26	32.44	72.16	32.48	41.94	56.19	0.10	55.66	41.05	28.25	28.25	27.00	26.86	Rt. 243
8.52	600.39	323.67	333.42	848.38	147.91	132.46	912.31	54.35	30.56	0.64	27.93	57.80	38.08	38.08	30.77	30.14	I-495
42.37	*0.18*	*2.48*	*3.20*	*0.19*	*7.98*	*8.12*	*0.21*	*24.89*	*33.81*	*0.13*	*0.06*	*0.06*	*0.06*	*0.06*	*33.67*	*0.06*	*Pre-Sim Freeway*
3.21	224.99	133.96	136.57	314.50	73.03	83.72	330.19	17.52	53.84	0.26	52.78	41.71	28.07	28.07	23.26	23.01	Avg.

Table D.5 - Simulated Time to Wait in On-Ramp Queue at 7:00 P.M. (Minutes)

Note: Combining the addition of a lane to the freeway and Weighted Fair Queueing (L + WFQ) was tested as a possibility, and results are listed in the tables above. However, I did not discuss this combination in the report as its performance was unacceptable and not worth any more discussion than that given to Weighted Fair Queueing alone.