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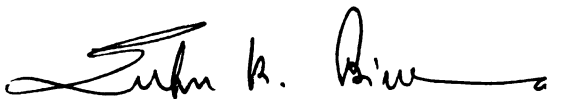
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**INFRASTRUCTURE-LESS URBAN TRAFFIC MANAGEMENT USING
VEHICULAR AD HOC NETWORKS**

By

Howard Vanlue Hardiman

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

MASTER OF SCIENCE

Electrical and Computer Engineering

2008

ABSTRACT

INFRASTRUCTURE-LESS URBAN TRAFFIC MANAGEMENT USING VEHICULAR AD HOC NETWORKS

By

Howard Vanlue Hardiman

This thesis develops an urban traffic management framework using distributed vehicle-to-vehicle communication and computing. Most of the existing vehicle navigation and route guidance systems rely on GPS-enabled location information, coupled with FM radio or cellular facilitated centralized content services. However, this mode of traffic management is expected to suffer from long term business scalability and reliability issues, due to its reliance on centralized paid services. As a consequence, the evolving technology of wireless vehicular ad hoc networks (VANET) is currently being perceived as a plausible communication platform for this application. Guided by this industry and research trend, this thesis proposes an infrastructure-less framework designed specifically for the purpose of traffic congestion alleviation and avoidance. In specific, the application layer algorithms have been developed, along with the underlying wireless VANET schemes suited for distributing the application layer induced traffic management information. The designed architectural components include mechanisms for congestion detection, broadcast based VANET routing for efficient congestion notification, vehicular transport oriented VANET routing used for connecting network partitions in sparse vehicular scenarios, and a constrained vehicle navigation algorithm for congestion mitigation. Extensive simulation studies have been performed, and the results indicate that the system is able to successfully manage vehicular traffic, while delicately handling the wireless broadcast medium.

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To My Family, Both On Earth And In Heaven,

For All Their

Love, Support, And Prayers

Acknowledgements

I would like to thank my advisor, Dr. Subir Biswas, for his unwavering patience throughout this project. Without your expertise and never-ending support, completing this work would have been impossible. As for my committee members, Dr. Percy Pierre and Dr. Jian Ren, thank you for being flexible in terms of organizing the defense aspect of my requirements.

I would also like to thank the CSE department and HPCC staff for providing and up keeping the HPCC. The HPCC definitely allowed the computationally intense vehicular simulations performed for this thesis to be run in a much more efficient manner.

I would also like to thank Dr. Percy Pierre and Dr. Barbara O'Kelly for all that they have done, in terms of my existence here at Michigan State University. Without their efforts within the realms of providing graduate education and assistance to underrepresented students, I am unsure how this portion of my career would have gone. Also, I would like to especially thank Dr. O'Kelly for all her efforts and administrative support.

As for my close friends who have stood by me, thanks for the support and companionship throughout my work and life.

Lastly, I acknowledge and thank the EE Aggies who made the trip up to East Lansing in the fall of 2005. Although things got rough and distance has come between us, each person has indirectly contributed to the completion of this work.

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KEY TO SYMBOLS OR ABBREVIATIONS

ADI: Adaptive Dissemination Interval

ASTM: American Society for Testing and Materials

DET: Data Expiration Time

DSRC: Dedicated Short Range Communications

DTA: Dynamic Traffic Assignment

EBT: Event Backoff Time

EWT: Event Wait Time

FAT: Forward Attempt Time

FM: Frequency Modulation

GPS: Global Positioning System

ICI: Initial Congestion Indicator

IEEE: Institute of Electrical and Electronics Engineers

MAC: Media Access Control

NTCC: No Traffic Congestion Control

RCI: Relative Congestion Index

TDV: Typical Delay Value

UDV: Updated Delay Value

VANET: Vehicular Ad Hoc Network

WiNDCC: Wireless Network assisted Distributed Congestion Control

ZOF: Zone Of Forwarding

ZOR: Zone Of Relevancy

Chapter 1: Introduction

The primary issue addressed in this project is one that affects most people and the modern society whose development is intricately predicated on the performance of the roadways they travel. For many years, the primary mode of transportation in the United States and various countries world wide has been the automobile. In other countries, automobile usage is rising steadily, just as it has in many of the ever growing U.S. markets. To account for the gradual increase that has taken place in terms of automobile usage and municipality development, roadways are built to connect people with places. As a consequence, the primary reason for the creation and upkeep of roads is to insure drivers a selection of viable paths to travel. This is especially so in urban areas, where the number of drivers, along with the increased amount of unique destinations to travel, is sometimes such that the existing roadways can not effectively accommodate all of them. Also, roads are built to connect newer areas to ones that are more established. Nevertheless, no matter the specific reason for developing a new road, circumventing the traffic congestion that takes place on all roadways is critical to the travel times and happiness of the motorists who use them.

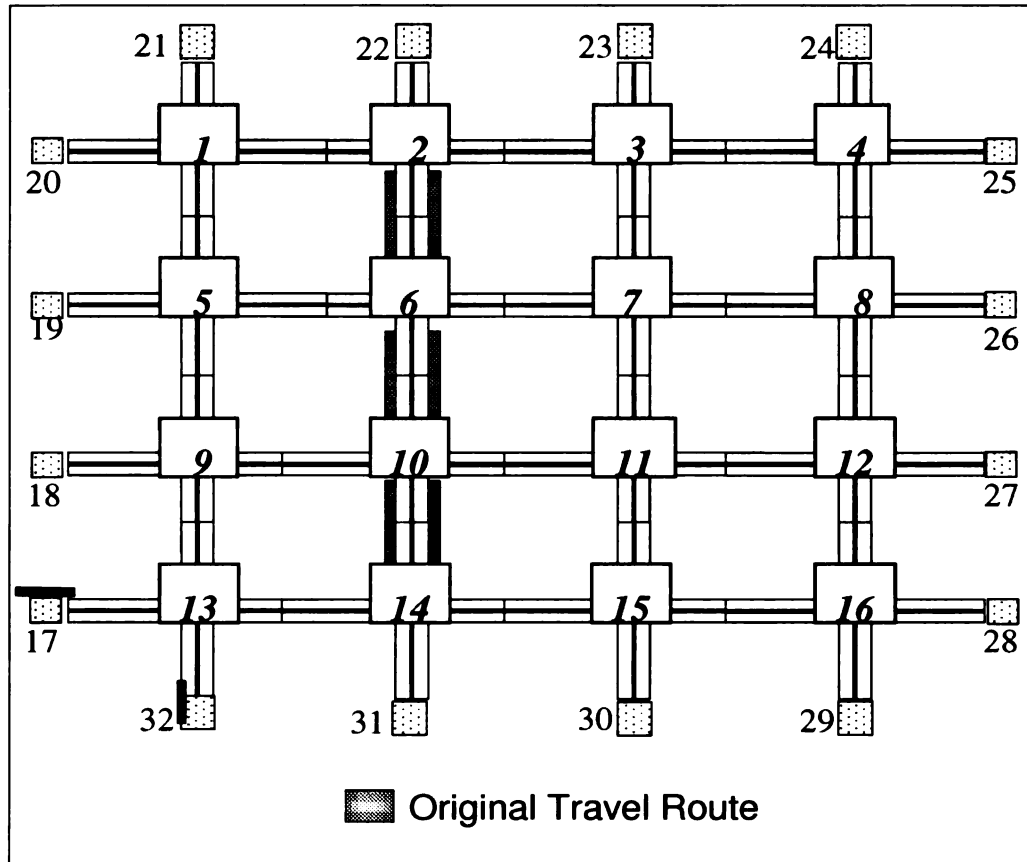


Figure 1-1: Sample traffic grid

1.1 Travel Choices in Vehicular Environments

To help illustrate and put into perspective the work done in this thesis, consider the basic grid traffic network found in Figure 1-1. For this discussion, consider the outer most squares, labeled 17 through 32, sources or destinations for drivers using this arrangement of roads. The inner labels, 1 through 16, represent intersections in which normal traffic light logic applies. Although simple in nature, a driver utilizing this network will face a problem similar to motorists traveling in any realistic traffic setting; that is, at each intersection a driver has a choice as to which direction to continue, based on their perception or knowledge of the potential roadways and the destination location. This perception is usually dependent on what one can visually see while traveling or his

general understanding of which routes are most efficient. For certain drivers, a path is usually set in stone regardless of the current traffic conditions. For others, consideration of the time of day or events is given, and a route is selected based on these observations. Some drivers use logic that involves aspects from both perspectives. As a consequence, these motorists use hard wired paths for traveling and only deviate from them when they can visually verify congestion taking place on the links they originally intend to travel. In this case, a certain degree of familiarity is required to execute efficient travel. Therefore, in instances when a driver is travelling in areas in which they are not familiar, these types of approaches can not be used since drivers do not know the exact consequence of making a particular travel decision. Nevertheless, for each of these types of motorists, there is an issue of whether or not the perceived traffic conditions represent those actually present on the roadways. As a consequence, the overall travel delay experienced by travelers is sometimes greatly increased, when there is some activity within the desired path that prohibits traffic flow at a normal rate.

For example, consider a vehicle utilizing the grid in Figure 1-1 traveling from intersection 31 to 22. Assume the driver of this vehicle will be taking the path he or she thinks is the best, traveling north at each intersection until reaching the destination labeled 22. This path is also highlighted in Figure 1-1. On an average, assume the travel time for this particular path is 4 minutes. That is, under the typical best case circumstances in which this network operates, 4 minutes is how long a motorist should expect to travel the road between intersections 31 and 22 in the northern direction. Furthermore, suppose this is also the optimal or fastest path for a driver destined for intersection 22, from the intersection marked 31.

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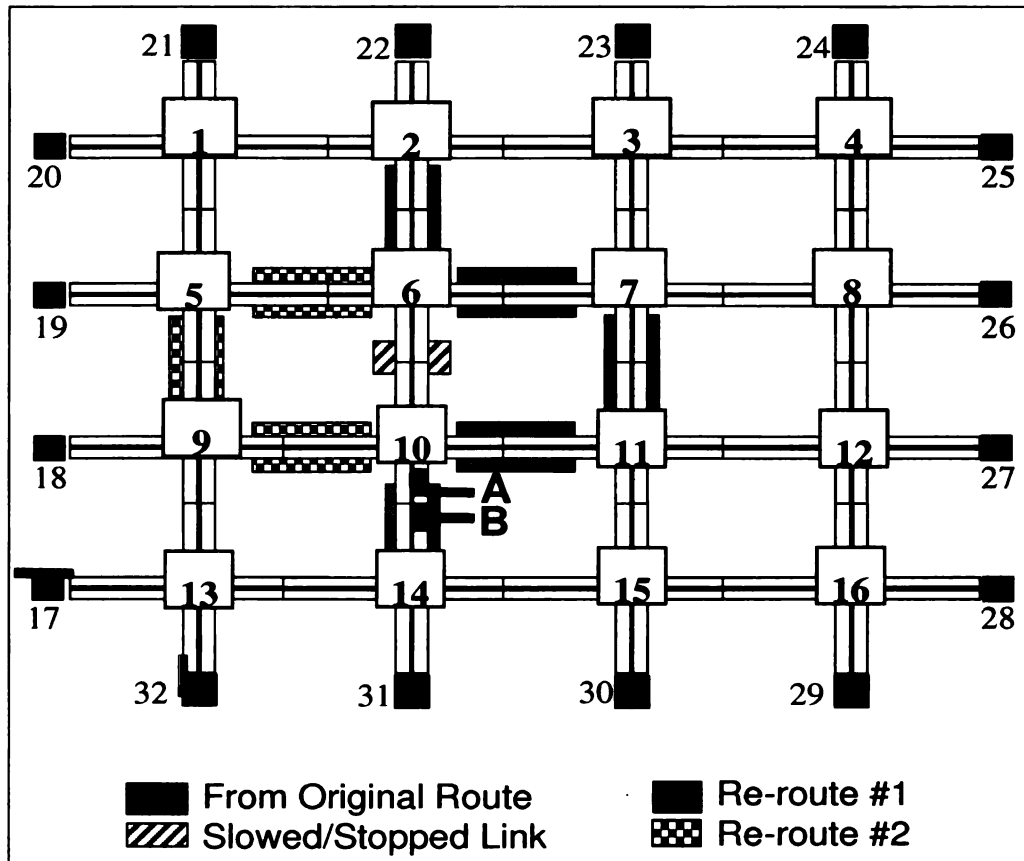


Figure 1-2: Incident with possible travel re-routes

Now, think about an event that slows or stops traffic within the link between intersections 10 and 6, Figure 1-2. If the traveler reaches this link between the time in which this event happens and that it is cleared up, he will be delayed during his trip; and, this vehicle will potentially arrive at the destination intersection after traveling a much longer time than the average, 4 minutes. Also, highlighted in Figure 1-2 are two of the many alternate paths a driver may well choose to utilize, based on its current position and that of the destination. However, depending on a motorist's knowledge of this particular traffic environment, they may not realize the available detours. Also, while utilizing one of these paths may allow the driver an opportunity to avoid the congestion issue, the path may also be blocked or there may be an advantage in using one path over the other.

There could also, amongst the set of possible diversions not highlighted on the map and the position of a vehicle needing to be diverted, be another route that could be superior. This blockage or link slowdown represents an inevitable and frequent aspect of vehicular travel.

The goal of this project is to create a completely distributed and infrastructure free vehicular ad hoc networking based application, network protocol, and specification to solve problems such as the aforementioned. Utilizing the basic principles discussed here, the motivation of this work can be found.

1.1.1 Delay vs. Distance Examination

When considering the issues presented in section 1.1 and the example traffic grid given, a key challenge associated with real time vehicular route modification system development can be realized. That is, assuming the system at hand is able to compute and deliver routes with the shortest travel delay under optimal traffic network performance, the vehicles that are taken away from that primary path to a secondary one will travel, in general, a longer distance than those remaining on the primary. It is an inherent issue associated with this problem, although travel delay mitigation can be achieved by moving vehicles away from congested areas. That can be seen by examining the distance of the highlighted secondary paths of Figure 1-2 and comparing the distance to that of the primary path, Figure 1-1. On the other hand, there may be instances where vehicles travel a shorter distance. In this case the secondary path is slower than the primary, resulting in the primary path being longer in distance but shorter in estimated travel time than a secondary route. For the sake of this discussion, assume that the primary path is not only faster in regard to time but also is shorter. However, the ideas

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and arguments still apply and will be briefly discussed for cases when a secondary path is shorter than the primary.

Reconsider Figure 1-2 and the scenario depicted, vehicles traveling from intersection 31 to 22 with a congested or stopped link between intersections 10 and 6. Once again, the primary travel path for this source and destination pair is as outlined in Figure 1-1, north at each intersection until the destination is reached. Now, to help put in perspective the delay versus distance tradeoff and its relationship to system performance, notice the vehicles marked A and B found in the link before the congested roadway. If the travel of these vehicles is under the influence of a route modification system, the mechanism may intend for them to be directed away from the primary path onto one of the secondary ones to evade the traffic congestion. However, it may also be most beneficial for them to remain on the primary path; in this case, the traffic congestion along the indicated link may not degrade the travel delay enough to warrant switching to a longer path. Dealing with the issue of whether or not a vehicle should switch away from the primary travel route, during times of slowed or stopped traffic, is key to overall system success. To understand why, assume that vehicle A remains on the primary path, while vehicle B switches to the path west of the congested link in an effort to avoid the traffic congestion ahead. Now, vehicle B will definitely travel a longer path to reach the destination. On the other hand, it is not guaranteed that it arrives at the destination sooner than the vehicle who has maintained the congested primary travel path, A. However, if they both exit their current link at relatively the same time, from an individual user perspective especially, it is most desirable for vehicle B to arrive at the destination sooner than vehicle A. That is, in order to completely warrant the switching of vehicle B to a

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longer travel path, vehicle B should be awarded with a smaller travel delay than a vehicle immediately in front of it utilizing the congested primary travel path.

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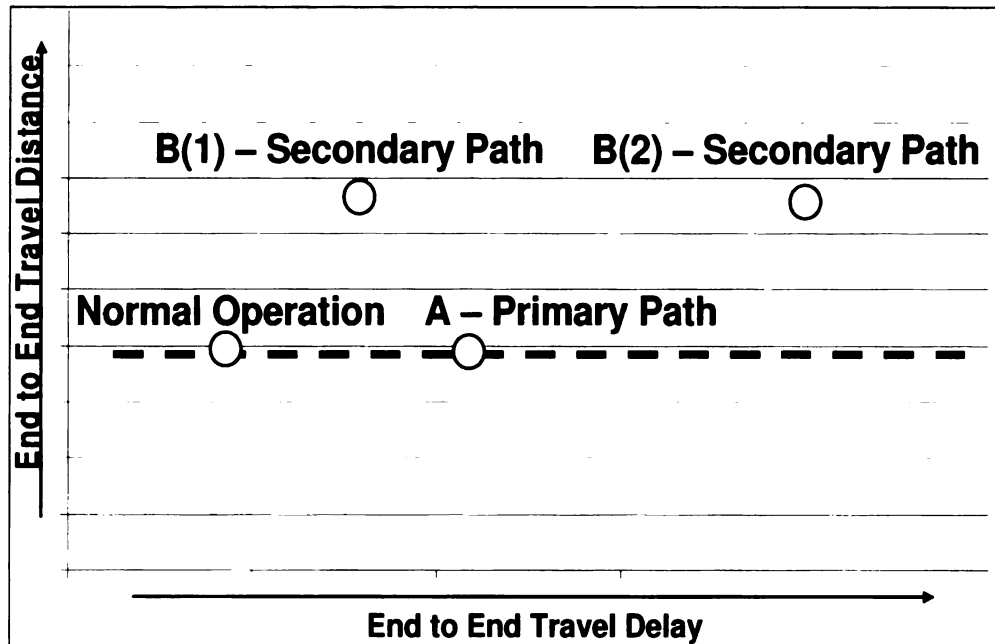


Figure 1-3: Delay vs. distance perspectives for vehicle A and B

Figure 1-3 helps put this idea into perspective. In this figure, the primary purpose is to determine if switching travel paths is justified based on the end-to-end delay and distance experienced by switched vehicles and those directly before them that don't switch. In the case of this example, it refers to vehicle B and A respectively. The x axis represents end-to-end travel delay while the y denotes end to end travel distance, and each of the data points represents the end to end delay and distance for the indicated vehicle. Farthest to the left, the normal operation data point represents the typical delay and distance of a vehicle utilizing the prescribed travel route under optimal traffic conditions. Notice it is located along the black dashed line, which indicates the travel distance of the primary path denoted in Figure 1-1. Compared to the data point for vehicle A, it is shifted to the left signifying that vehicle A utilizes the primary path during a period of congestion, as the example suggests. In regard to the possibilities for vehicle B, two potential points are included to highlight the importance of appropriate switching,

B(1) and B(2). Both points are located above the dashed line, representing switching to a longer path to avoid the congestion that vehicle A experiences. However, point B(1) is to the left of A and B(2) is to the right. Since this indicates a smaller travel delay for vehicle B, point B(1) would represent a justified instance in which vehicle B changes to a longer travel path. B(2) signifies an unjustified or inefficient switch since B would travel a longer distance and have a greater travel delay than vehicle A. The analysis of path switching during times of congestion can be analyzed by viewing a diagram such as this.

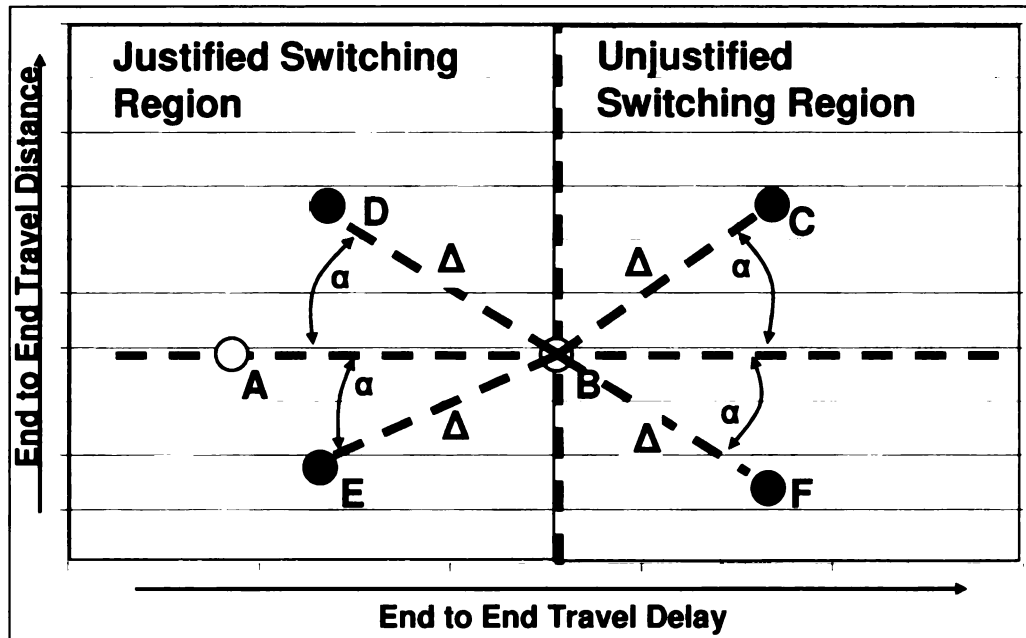


Figure 1-4: Generalized delay vs. distance perspective

To summarize the consequences of switching away from a primary path during instances of congestion, examine Figure 1-4 and assume each data point pertains to vehicles sharing the same starting and destination link. Here, point A represents the optimal average delay and distance of a vehicle traveling the primary path, denoted again by the dashed line. As a result of a vehicle B traveling the primary path with congestion present, its data point is moved farther along the delay axis while remaining on the same dashed line as A. Points C, D, E, and F are possible representations of a vehicle that immediately follows vehicle B, but switches away from the primary path due to perceived traffic congestion. If point C or F represents the distance and delay of this vehicle, the vehicle has arrived within the unjustified switching region, since it has switched paths and arrived at the destination later than vehicle B. If point D or E is representative of the distance and delay of this vehicle, then switching is justified since the vehicle in question arrives at the destination sooner than vehicle A. Note that points

C and F indicate paths that are shorter than the primary path but longer, on average, in terms of delay. Nevertheless, the main goal of a traffic route adjusting system should be to only switch vehicles away from the primary path when the mechanism is most sure the vehicle will be delivered within the justified region, in comparison to a non-switched vehicle. By utilizing the depicted quantities α and Δ the argument can be furthered as follows. For vehicles with characteristics similar to D, taking a longer path than the primary but showing delay improvement, the mechanism should look to decrease the angle α while increasing Δ . In the case of an arrival like C, the goal is also to decrease α but Δ should be decreased. For vehicles like E, taking a shorter path than the primary but showing delay improvements, the goal is to increase both α and Δ . The goal for a vehicle, such as F, traveling a shorter distance than the primary path but a longer time than the reference vehicle A, is to increase α and decrease Δ . By utilizing these principles, one can see the importance of switching vehicles during appropriate times when designing a system meant to choreograph traffic during times of congestion or otherwise.

1.2 VANET Basics and Applications

The Vehicular Ad hoc Network (VANET) has developed into a mature research space. In regard to vehicular technology in general, the idea of incorporating ad hoc networking principles and capabilities adds to an already rich set of application capabilities being offered by auto makers. In short and as opposed to current communication tactics used by vehicle and in car communication device manufacturers, ad hoc networks will allow high speed connectivity on a vehicle to vehicle and vehicle to roadside station basis [1]. That is, intelligent vehicular communication devices will be

able to communicate with roadside stations and other vehicles on a one or multi-hop basis [1, 2], while current wireless vehicular communication exists strictly between vehicles and centralized entities [3]; As a consequence, the vehicular devices do not communicate directly with one another. A brief look at the applications enabled by vehicle to vehicle communication is as follows.

1.2.1 Travel Improvement and Safety

For obvious reasons, a healthy amount of VANET applications fall into the category of safety or travel improvement. To clarify, the travel improvement breakdown describes applications that assist motorists in the day to day situations encountered while driving [4-8]. Also, included are safety applications designed specifically with the safety of drivers in mind [4, 9, 10]. In terms of implementation, most of these services are accomplished by vehicle to vehicle communication as opposed to vehicle to roadside [11], although some utilize the aid of base stations. This is due to the time pertinent nature of the messages being exchanged. By extending some of the one hop sensor based safety applications currently found within the vehicular industry, the advantage of using VANET travel improvement technology can be found. For example, currently sensors can alert drivers of vehicles exhibiting sudden decreases in speed directly in front of them. However, under a VANET based scheme [6, 9, 10], motorists can be alerted of stopping or rapidly slowing vehicles much farther ahead of the car preceding it. Other systems assist groups of vehicles by indicating collective travel speeds to assist in vehicular smoothing or cruise control [5, 7, 12]. In fact, the topic of works such as this thesis is also included within the range of travel improvement and safety and will be

discussed in greater detail in the related works section. In regard to travel improvement and safety, the VANET space provides various relevant applications.

1.2.2 Leisure Applications

Aside from the travel improvement and safety applications implemented by the VANET framework, leisure applications are also relevant. Most of them include providing internet access to drivers via the VANET enabled in car devices. Therefore, it can be understood why internet gateways or roadside stations usually accompany the implementation of these sorts of systems [11]. Additionally, other applications utilizing vehicle to vehicle and vehicle to roadside functionality include shopping, gaming, and marketing for business and other services relevant to travelers [13, 14]. Although not the category relating to the work presented in this thesis, internet and other leisure services are actively being considered from an application and lower layer networking perspective.

1.3 VANET Oriented Route Guidance System

The topic of this thesis combines the abovementioned principles to create a system capable of detecting and correcting traffic congestion issues. As previously mentioned, this system would fall into the application arena of travel improvement and safety. Regarding the basic implementation principles for the system developed in this thesis, Wireless Network enabled Distributed Congestion Control (WiNDCC), the mechanisms and protocols do not require the assistance of any infrastructure or centralized entities. Instead, traffic delay mitigation is achieved by utilizing the VANET on a strictly vehicle to vehicle basis. That is, the gateways utilized by most applications within the leisure

subset will be unneeded by WiNDCC. Therefore, with respect to the traditional wireless network system architecture components, WiNDCC protocols reside within the network and application layer. In the related work section, similar VANET oriented systems will be discussed.

1.4 Current Route Guidance Systems

In regard to the current offerings of automobile and in car navigation device manufacturers, route guidance or congestion avoidance packages are available. Unlike WiNDCC and other VANET based solutions, these systems rely on centralized data locations to store and relay the traffic information to equipped vehicles. Also, they do not utilize other vehicles to assist in the probing and transmitting of data. Instead, the centralized entities communicate directly with subscribing vehicles. In terms of the communication mediums utilized, there are a few that are used to transmit traffic data to users [3]. Traditional cellular networks, newer FM radio links, and satellite connections, are the current standards used to get the traffic updates to drivers. As noted in the article, the performance of these systems is sometimes unpredictable and subject to high delay, with respect to the timeliness of receiving the traffic status of a particular link.

With respect to VANET solutions for the problem of traffic congestion mitigation, the delay and accuracy of information could be greatly improved. That is, since vehicles communicate with one another, traffic congestion can be readily identified and broadcast specifically to the relevant devices that need them. However, the current offerings, although somewhat limited, prove to be useful to the motorists who equip the devices.

Chapter 2: Related Work

In general, the literature related to this work is directly in line with the multi layer solution proposed in WiNDCC. Since the overall system is enabled by utilizing navigation devices, presented first are a class of papers that relate to the evolution of in car hardware systems and challenges in general. Then, in accordance with the main system goal of alleviating travel delay in vehicular environments, works that deal specifically with this task are discussed; here, VANET principles are not incorporated.

Finally, since the route guidance system presented in this thesis is implemented by the VANET framework, manuscripts particular to VANET principles and challenges will be discussed. Relating to the layers in which WiNDCC operates, VANET network layer papers particular to WiNDCC operation will be covered, along with VANET oriented application layer systems designed for route modification and travel delay mitigation.

2.1 Onset of in-Vehicle Devices

In regards to the current product offerings within the realm of vehicular navigation systems, both manufacturers installed and off the shelf navigation units are becoming more readily available and used within the end user domain. However at the onset of their development, work was committed to understand the hardware, software, application capabilities, and other design issues characteristic to such a device.

2.1.1 The Need for Position Information

One of the core requirements of any vehicular navigation or service device is that the devices understand and use the information relating to its own geographical position. This need is common in various application domains, not only within vehicular context.

In [15], the integration of two position determining implementation schemes is combined to form an accurate method of determining position within the vehicular context. The two methods are Global Positioning System (GPS) and dead-reckoning; GPS uses satellites as reference positions to determine position, and dead-reckoning uses heading and distance sensors to measure displacement vectors that are used in a recursive manner to determine vehicle position. Discussed in the manuscript are the various limitations of each scheme and the way in which combining the two results in superior performance. Results and analysis relate to the efficiency of each individual position acquirement method. Other results show how the combined system is able to recover from the errors in which the two schemes present individually. From an implementation perspective, the topic and conclusions from a work such as this are seen on a wide scale basis, especially within the in car navigation device domain.

2.1.2 In Car Devices and Driver Interaction

In [16], one of the initial perspectives into the viability of in car systems is given, with respect to human interaction. This sort of report is important because, while striving to improve driver satisfaction by using visual or auditory navigation devices to assist with certain tasks, designers must be aware of the consequences associated with actual motorist interaction. That is, although navigation devices may aid drivers at certain driving tasks, the usage of such devices could produce severe hazards within the traffic environment by taking the attention of motorists away from the road. By way of an intense simulation study, several performance indices were measured including heart rate, speed, and navigational errors seen when subjects were utilizing one of a few navigation interfaces. Overall, the age of subjects affected their performance, with younger people

faring better than older, in terms of safely using their assigned navigational device. Also, of the navigation devices used, subjects tested with the more complex of the devices drove more slowly; This is to be expected since most drivers typically slow down to process information when driving, and the more complex device differed from the others by introducing much more navigational messages to the test subjects. In terms of understanding how drivers of different ages will react to navigational devices of varying complexity, with respect to various performance indices, this work presents some preliminary data that encouraged the development for the devices available today.

2.1.3 An Early Driver Information System

As a basis for the FM radio based [3] dynamic traffic routing systems seen today, this work creates a hardware and software framework, called TravTek, capable of utilizing the communication medium for the purpose of probing traffic information and guiding vehicles according to it [17]. As a consequence, the goals of the TravTek driver information system are very similar to those of the WiNDCC framework presented in this thesis. The study involves the implementation of 100 vehicles within Orlando Florida, and investigates the usage of a centralized traffic management center connected to the in vehicle devices via the FM radio link. At the time of this effort and especially from a hardware perspective, the design is obviously restricted to the usage of the technology of its time. However, the built upon principles are very much at the heart of current route guidance systems and WiNDCC, although WiNDCC incorporates additional logic meant to assist in determining when delay information should be extracted. That is, vehicles begin by utilizing nominal travel time information to determine the suggested travel route, depending on a vehicles current position and that of the destination; particular to

the task of position awareness, this is accomplished by using global positioning satellites, just as it is in newer navigation systems. Then, as updates are received regarding relevant travel links, the system re-computes travel routes based on them. In terms of a functional breakdown, the authors describe each component individually including route selection, driver interface, data logging, route guidance, and a data base responsible for storing establishment destination specific information for a particular geographic region. Considering the system goals and implementation scheme of such a system, this translates to a centralized dynamic route computation framework with GPS and FM radio at its position awareness and communication backbone. The main ideas of this work are important and are being utilized today in terms of the delay mitigation and route notification tactics utilized in today's navigation devices [3]. In addition, one can find similarities between TravTek and the proposed mechanism, WiNDCC.

2.2 VANET Networking Challenges and Solutions

A work outlining some of the challenges of VANET design and implementation is as follows [18]. The authors begin by highlighting a few typical issues associated with random waypoint induced mobile ad hoc networking in general, the superclass in which the VANET is based. Then they compare the applicability of these issues within the context of the VANET or inter-vehicle communication (IVC) realm. Finally, the paper discussed the design implications associated with the VANET. A close look at this work will be given, as it describes the difficulties and challenges associated with designing a system such as WiNDCC.

Some of these issues, from the perspective of the link layer, include the hidden and exposed terminal problem. Here, because of the positions of communicating nodes, connectivity and throughput is adversely affected.

From the routing or network layer outlook, three broad classes of ad hoc networking routing protocols are identified. Table-driven, source-driven, and position-based routing strategies are the identified breakdowns. Table-driven routing protocols are proactive in the sense that each node attempts to maintain a current representation of the network topology. Contrarily, source-driven protocols are reactive in the sense that routes are requested by source nodes only when needed. In terms of position-based routing protocols, a location service may be needed to find the location of a destination node. These protocols, the authors mention, naturally support services in which the set of recipients is defined as nodes located in some target region of space.

In reference to security, the authors note that because the mobile ad hoc network lacks infrastructure, securing it is very difficult. However, by way of cryptographic routing techniques, redundancy based secure message transport, and intrusion detection paradigms, the mobile ad hoc network research space contains various works intending on securing the networks. Cryptographic routing techniques increase network overhead by including cryptographic information responsible for validating routing messages. Secure message transport takes advantage of multiple paths between source and destination nodes to ensure data messages are not compromised. Intrusion detection schemes use packet overhearing to be sure malicious information is not propagated throughout the mobile ad hoc network.

After describing the principles pertaining to the mobile ad hoc network, a simulation study was performed based on a sample traffic scenario to understand some of the differences between the mobile ad hoc network and the VANET. The primary differences are described in full detail.

The first fundamental difference relates to the rapid changes in the network topology seen within VANETS. These changes occur despite the fact that vehicles must remain on the roadways and cannot venture completely randomly in a particular geographic area, therefore somewhat restricting their mobility. In addition, the topological inconsistencies are caused by the high relative speed of vehicles and can be predictive when considering the traveling direction of vehicles. That is, the links created by vehicles moving in the opposite directions are shorter lived than those between vehicles traveling in the same direction. The authors also mention that, although this degrades performance in relation to other metrics, increasing radio range helps increase the connectivity and decrease the changes within topology.

The second highlighted difference between the mobile ad – hoc network and VANET deals with the frequent fragmentation of the network, in which chunks of the network are unable to reach nodes in nearby regions. This effect is motivated by the slow introduction and penetration rate associated with the onset of VANET technologies; the scenarios presented are based on the optimistic goal of having VANET enablement in 20% of vehicles. Once again, the costly practice of increasing radio range does decrease the fragmentation.

Thirdly, the effective network diameter in a VANET will typically be very small, in comparison to the traditional ad hoc network. This is because the routing paradigms used

within the mobile ad hoc networking realm are rendered much less effective within the VANET, because of the topological inconsistencies and rapid changes involved with this system. Therefore, the effective network diameter is inconsistent and decreased. That is, since proactive routing keeps data relating to the full network topology, it is very difficult to do so in the every changing topology of the VANET. Also, reactive routing suffers since a path may cease to exist almost as quickly as it was discovered.

The fourth difference speaks about the lack of redundancy found within the VANET. Since multiple paths cannot be readily had between sources and destinations, the abovementioned security mechanisms, and other protocols utilizing this requirement, would not be relevant in this sort of network. As a result and as previously mentioned, increasing the radio range could assist in this effort. However, doing so will increase the number of exposed nodes and decrease throughput by introducing a larger interference radius.

Finally, when considering the abovementioned issues, the authors discuss some of the design implications that must be addressed when working within the VANET space. At each layer, considerations must be made in order to establish and maintain usable connectivity for the applications implemented by the VANET. At the physical layer, different frequency bands, the usage of roadside infrastructure, and directional antennae are mentioned as ways to assist in the design of these networks. At the link layer, it is suggested that decentralized time slots or spectrum be used. Routing layer operations would be benefited by using location based schemes, which must be specially tailored for the VANET. In terms of security, it is suggested that adding roadside receivers could allow for the VANET to utilize some of the security schemes seen within the mobile ad

hoc network. However, it is acknowledged that the security issue is one that is very difficult to solve within the VANET.

With respect to these challenges, the WiNDCC system is designed to work amidst in as efficient manner as possible.

2.3 WiNDCC Contributing Protocols and Considerations

In terms of the WiNDCC system presented in this thesis, it has flavors from various route guidance, link travel time estimation, and VANET routing and application layer paradigms. This section is broken down in terms of the main WiNDCC operational components and the relevant literature contributing to each will be discussed.

2.3.1 Application Layer Functionality

In terms of the WiNDCC system developed for this thesis, the high layer application layer goals have been described in section 1.1 and relate to mitigating congestion and traffic delays in vehicular environments. In reference to how the system aims to solve these problems, a few works should be referenced.

In [19], a simple Dynamic Traffic Assignment (DTA) model based on real-time local-feedback information is introduced. When considering the goals of this system, they are very similar to WiNDCC. However, the traffic sensing and transmission schemes are much different. The specification uses information collected from lane embedded sensors to determine the status of the traffic environment. In addition, the authors suggest three main assignment techniques for the purpose of rerouting traffic during instances of congestion or otherwise. The first, a stochastic assignment method, perturbs the link costs within predefined limits to randomize the route selection process

for a vehicle. The second uses global feedback assignment, a scheme which assumes that drivers who are familiar with the road network will reroute if information on the present state of traffic conditions is fed back to them. Lastly, the local feedback assignment model presented is based on real-time local information that is designed to produce reasonably accurate results with a minimal number of parameters and computational effort. That is, the model acquires only the real-time data on link costs for the next links out of the current intersection and decides which turn to take based on this localized information. As for simulation setup, the authors use a mock traffic network and track the end to end travel delay associated with each vehicle. Since the information is assumed to be acquired by way of sensors embedded within the lanes and the traffic information would then need to be gathered, edited, and relayed back to vehicles, the effect of time lag is studied.

The results show by comparing the feedback and stochastic assignment methods, the random assignment method fares better than the global feedback when the time lag is greater than 2 minutes. However, the local feedback fares better than the stochastic regardless of the time lag quantity. Then as a second experiment, the effects of incidents are examined according to the three assignment methods. It can be seen that the delay values under the feedback assignment methods converge, while the stochastic method brings the traffic network to unstable. As a conclusion and under the typical 5 minute time lag associated with gathering information from lane sensors, the local feedback assignment method proves to be the more effective of the assignment methods used. As a result, WiNDCC along with other dynamic route modifications systems also inherit a

feedback oriented traffic response paradigm. However, the effect of time lag is much less than that assumed in this paper.

In [20], the authors examine how much individual traffic data is needed in order to obtain reliable traffic information for a certain road link within the VANET. The authors examine works that exploit the central limit theorem to develop minimum sample sizes. However according to the central limit theorem definition, data would either need to be normally distributed or there must be a very large amount of non-normal data. However, travel time data are unlikely to be normally distributed, although during uncongested times this may be so. Therefore, during times of congestion, these methods may invalidate the central limit theorem and produce incorrect sampling sizes. This work introduces an acceptance probability that operates independent of a distribution, unlike the central limit based schemes. It uses the median of all individual data within a time window centered on the time instant in question as a proxy for actual information. The results of a simulation study show that the acceptance probability based extractions better represented the actual traffic conditions during times of congestion than the central limit theorem based schemes. Otherwise, both methods performed similarly. WiNDCC takes into account the spirit of the arguments and results obtained in this paper in its own sampling and delay message creation scheme. However, the system uses much less complex foundations to determine when to sample a links estimated delay time, while looking to minimize the overall number of extractions.

Another work which contributes to WiNDCC application layer functionality is as follows [21]. Here the authors examine the problem of forecasting future link travel and network congestion conditions. The authors argue that under the influence of a dynamic

traffic assignment scheme that uses perceived traffic network information to influence the travel of vehicles, the original free flow forecasts used to compute routes are invalidated. As will be seen in the WiNDCC formulation, this phenomenon is inevitable and is not necessarily a problem with respect to overall system operation. In fact, it will be hinged in terms of overall system operation and performance. Also presented in this paper is a key concept in regard to WiNDCC system operation. The authors compare by simulation the effects of forecasting link travel times as a function of vehicles entering a link or the exit delay values associated with vehicles exiting a link. Their results show that when considering the link exit delay measurements, the delay performance is better behaved and improved. Therefore, in Chapter 3 it will be seen that WiNDCC uses this results in its system development.

2.3.2 Network Layer Functionality

Simply stated, the WiNDCC network layer goal is to propagate the information generated and received as efficiently as possible to the vehicles that need it. In terms of the resulting implementation, there are a few works that contribute to the WiNDCC routing layer solution.

It will be revealed in Chapter 3 that certain generated packets will be forwarded away from the origination point as fast as possible by the WiNDCC network layer. In [22, 23], a mechanism is introduced and used that tailors specifically to this goal. Presented is an approach to distributing messages among highly mobile hosts in ad hoc networks. The approach focuses on using direct radio communication between moving vehicles on the road that requires no additional infrastructure. To better understand the strategy, consider the broadcasting nature of radio waves. Multiple receivers can receive

the same packets simultaneously. Therefore, determining when and how to forward messages is important, as various issues arise if this is not carefully handled, as seen in [24]. The authors of this work assume that any received packet contains the position of its sender, by way of navigation system. Then, by knowing its own position, a receiver determines the amount of time it will wait before forwarding a packet based on its distance from the sender.

$$WT(d) = -\frac{MaxWT}{Range} \cdot \hat{d} + MaxWT$$

$$\hat{d} = \min\{d, Range\}$$

MaxWT: maximum waiting time

d: distance

Range: transmission range

Figure 2-1: Distance based back off scheme of [22, 23]

This determination is made according to the equation listed in Figure 2-1. According to this formula, the waiting time, WT, is shorter for more distant receivers and longer for farther ones. The aim of using this mechanism allows their proposed system to disseminate messages quickly and efficiently around the area surrounding the vehicle. WiNDCC uses the concept of distance based back off to assist in propagating its own delay notification messages. Other works acknowledging a distance based back off scheme to assist in message forwarding operations within the VANET are [25] and [26].

Aside from moving messages as far from the origination as fast as possible, the WiNDCC mechanism also calls for vehicles to store and forward messages. This is done to assist in moments where there are network partitions prohibiting the movement of a piece of data beyond a certain vehicle. In [27], the authors make use of the concept of carry and forward, where a moving vehicle carries a packet until a new vehicle moves into its vicinity and forwards the packet. The mechanism developed is different from existing carry and forward solutions by making use of the predictable vehicle mobility, which is limited by the traffic pattern and road layout. They present several vehicle assisted data delivery protocols and results for each one. In terms of the WiNDCC

system presented in this thesis, the routing layer functionality calls for a geographical aware store and forward functionality, a simplistic rendition of [27]. Other works utilizing a trajectory aware store and forward approach are as follows [26-28].

Another contribution is important to WiNDCC network layer functionality. In terms of wireless network efficiency, one will find various WiNDCC protocol and system nuances designed to keep the wireless channel useable and free from the effects of redundancy, contention, and collision [24].

$$\text{Upper bound on transmission interval} = \frac{2R}{k \bullet (v_1 + v_2)}$$

R: transmission range

k: a value greater than the ratio of maximum velocity to average velocity of a road segment

v₁, v₂: average velocity for each travel direction

Figure 2-2: Sufficient transmission interval from [29]

This work [29] creates an adaptive dissemination mechanism for a decentralized traffic information system that causes each vehicle to adapt their transmission interval according to the current traffic speed. The specification also disseminates the traffic information of different segments at different rates according to the distance from its current position. In terms of network capacity and utilization, the scheme ensures efficient distribution of information within the vehicular network. The authors assume, similar to WiNDCC, that vehicles calculate their own link travel times and periodically broadcast its travel time spatio-temporal database to other vehicles. Other vehicles will receive this information and will include new data into their own spatio-temporal database. In particular, WiNDCC borrows an expression from this work primarily responsible for the efficient dissemination goals, Figure 2-2. Given R , k , v_1 , and v_2 , a vehicle can calculate the maximum transmission interval needed to inform passing vehicles of any information it has. That is, if a vehicle transmits at intervals less than that indicated by the expression, it will be possible to communicate with any mechanism equipped vehicle running in the opposite direction and the required bandwidth will be

much lower than the channel capacity. It will be seen in Chapter 3 that WiNDCC takes advantage of this expression in its own dissemination practices.

2.4 Agent-network Based Route Guidance System

In this paper [30], the authors introduce an intelligent route guidance system based on agent-network, which can automatically guide vehicles by voice. The work is presented in a section separate from the others because it presents results similar to those produced for this study. That is, the primary results deal with the delay mitigation associated with system usage and the distance trade off that occurs due to this mitigation. However, the implementation of their system is very different from WiNDCC. Particularly because this system utilizes, in each road segment, an agent which is responsible for fusing the data collected from sensors, calculating routes and segment costs, and communication with other agents to gather global traffic information. Contrarily, WiNDCC operates strictly on a vehicle to vehicle basis, eliminating the need for any agent or traffic network infrastructure. Nevertheless, the agents create a wirelessly or fiber optic enabled back bone computing platform that is responsible for receiving the information from road sensors, receiving the request from vehicular devices, and calculating the travel routes to be reported to drivers, as well as transmitting them via the author recommended Bluetooth links. The paper describes a simulation scenario that uses a grid network. Results are shown proving, that without their mechanism and system in place, the overall travel delay is worsened. It can also be seen that when the mechanism is equipped, the end to end distance is degraded, subject to the argument presented in section 1.1.1. This work is important because it presents results

similar to those found in this work, while also suggesting the usage of wireless devices and principles to assist with the process.

Chapter 3: WiNDCC Framework

In this chapter, the Wireless Network Distributed Congestion Control (WiNDCC) algorithms and system specifications will be discussed. In short, WiNDCC is a completely distributed, infrastructure and hello message free, vehicle to vehicle system designed for the purpose of meeting the traffic network goals explained in section 1.1. Here, a detailed description of the distributed wireless mechanism responsible for generating and propagating the protocol messages, needed to attain overall system responsiveness, will be given.

The chapter is organized in the following manner. First, a generalized look at WiNDCC goals and objectives will be discussed. Then, a system and network architectural view will be given. Next, details will be presented about the way the utilized navigation function computes paths based on the acquired information. Finally the core of the WiNDCC system will be detailed, which corresponds to the message generation and forwarding procedures.

3.1 Problem Discussion With Respect to VANET Oriented Solution

In terms of the system goals outlined in section 1.1, the WiNDCC system must be able to solve those issues, subject to the typical design barriers associated with the VANET [18]. As a result, the WiNDCC design exhibits careful treatment of the wireless channel in order to maximize its usage and maintain its integrity for other applications using the channel.

3.1.1 Network Overhead

The amount of packets generated by any protocol existing within the VANET domain is important to maintaining the health of the underlying wireless network. As a consequence, WiNDCC only transmits messages as needed within the vehicular environment. The basic rationale behind this action is as follows. If there is not traffic congestion in the traffic network, by some definition of congestion, then it is not necessary to transmit information about it. Because, in line with the system assumptions to be discussed in a subsequent section, the superior travel path under optimal network performance is available to each equipped vehicle. Therefore, if there are not issues within the roadway network, the vehicles should always follow this path. The primary question then becomes when to broadcast information about a link and how to do so. By using this principle, the WiNDCC system differs from others that demand vehicles have constant knowledge of the velocity, direction, and travel plans of neighboring vehicles, by way of hello message exchange [8]. Also, since the WiNDCC mechanism uses the communication medium in a broadcast only fashion, there is not a need for any routing overhead. Sending broadcast messages is more efficient than unicast messages, gaining even more with increasing network density, as a single transmission can reach more vehicles; even if a particular piece of information is not useful for a node, it can assist in further dissemination of the data unit [31]. WiNDCC works to reduce network overhead, while meeting the overall system goals.

3.1.2 Delay Message Propagation Needs

In the abovementioned section, the main issue is when to generate and broadcast information about the links within the traffic network. In terms of propagation needs, the

question is where and how to transmit the generated messages. Again, because the area in which a message is propagated interferes with the channel within that area, this is important as it relates to network overhead. The WiNDCC system addresses this issue by only transmitting delay messages to the vehicles within the areas of the traffic topology that need them most. Therefore, upon the initialization of a delay packet and based on the position and direction of the link being reported, the general propagation area is set. This assists in terms of wireless network utilization by limiting the area in which delay messages travel. When considering all of the potential delay messages extracted from vehicles using a severely congested traffic network, this simple action proves to save bandwidth on the wireless channel. In reference to how the messages are broadcast to these areas, a method is hinged to move the information amongst the prescribed relevant areas as fast and with as few packets as possible [22]. However, if the network is partitioned and this path is incomplete, other methods [22, 28] are manipulated to assist with propagation. WiNDCC propagates messages in a way that uses radio communication to initially and expeditiously move messages away from origination points and targeted message carrying and forwarding otherwise.

3.2 WiNDCC Architectural Perspective

From an architectural point of view and aside from any networking principles, there are a few components involved in WiNDCC operation. Also according to the traditional wireless network architecture, WiNDCC has its own specification that highlighted the functional entities responsible for the networking operations.

3.2.1 Functional Entities and Data Exchange

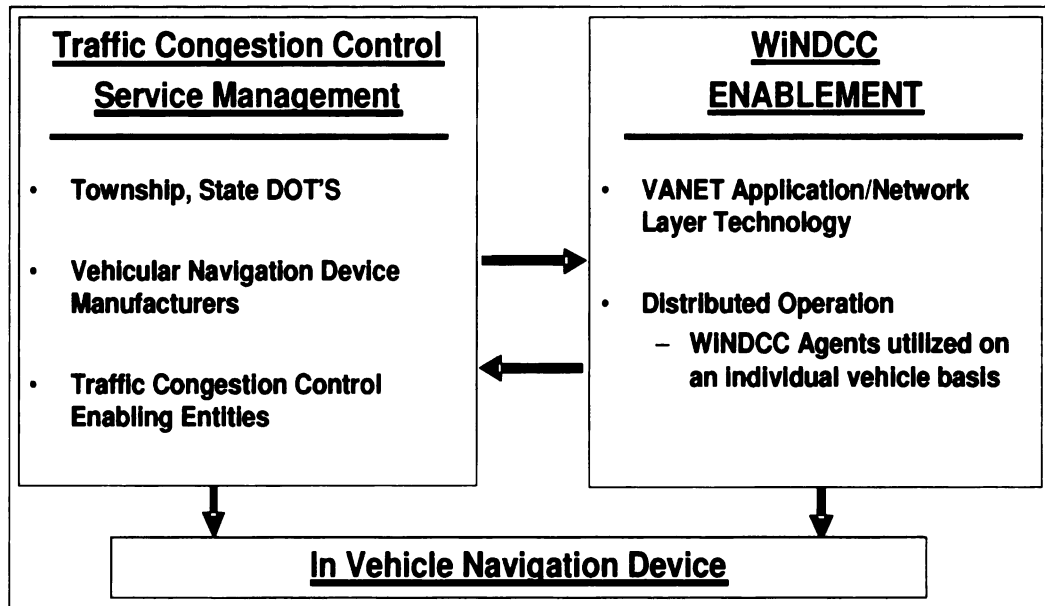


Figure 3-1: Basic functional entities and their interaction

In terms of the functional entities and devices responsible for influencing and implementing the WiNDCC system, they are highlighted in Figure 3-1. The diagram helps put into perspective the conceptual operation of VANET applications in general, as typically there is an entity that manages or enables the technologies implemented via wireless networking. The leftmost box designates this service management entity particular to this system, which includes all system participants besides the end users themselves. That is, the service management breakdown describes the groups responsible for enabling the application, in this case WiNDCC. For the purpose of supplying system critical inputs, state and local municipalities are included within the service management category. Indicated by the arrows, the service management and WiNDCC enablement exchange information in regards to the task of traffic delay mitigation. The WiNDCC enablement represents the in car VANET enhancements, protocols, system specifications, and definitions presented in this thesis. The in-vehicle

navigation device makes use of the information from both the service manager and WiNDCC to instruct drivers of the most viable travel paths given the current vehicular position and destination.

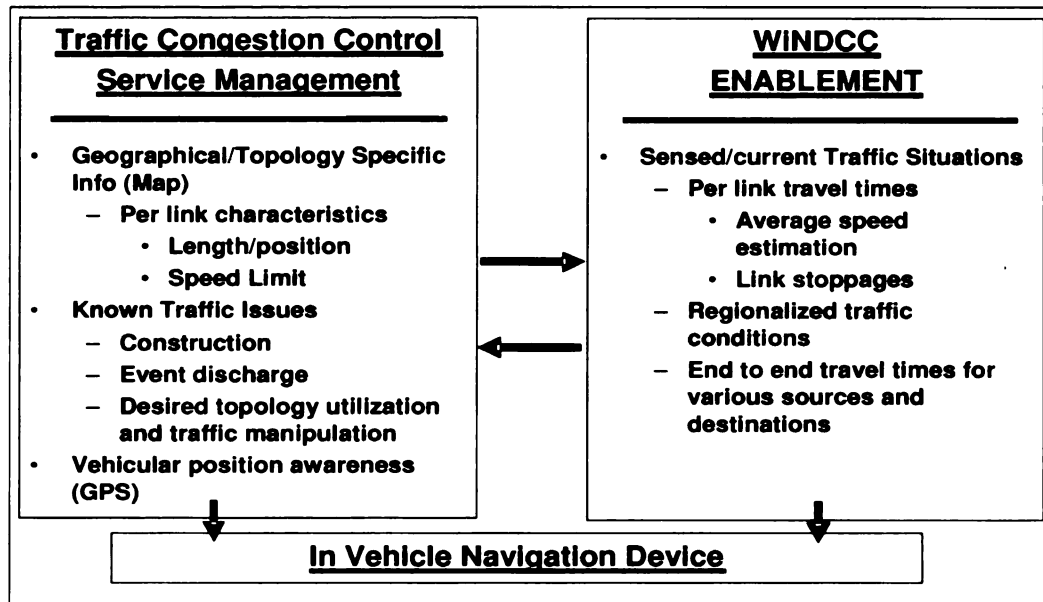


Figure 3-2: Service management and WiNDCC data exchange

To better understand the possible information exchange between the service management and WiNDCC system, examine Figure 3-2. In this diagram, the data exchange is summarized and overall system interaction can be seen. Namely, the service management entity is responsible for supplying the map data, free flow traffic times, traffic events, and the positioning information needed in order to make WiNDCC and the navigational aspect work. In return, the WiNDCC system can report traffic conditions back to the service management layer for analysis and forecasting purposes. Nevertheless, as will be seen in the mechanism description, the information WiNDCC receives from the service management entity is important to the systems operational goals.

3.2.2 WiNDCC Network Architecture

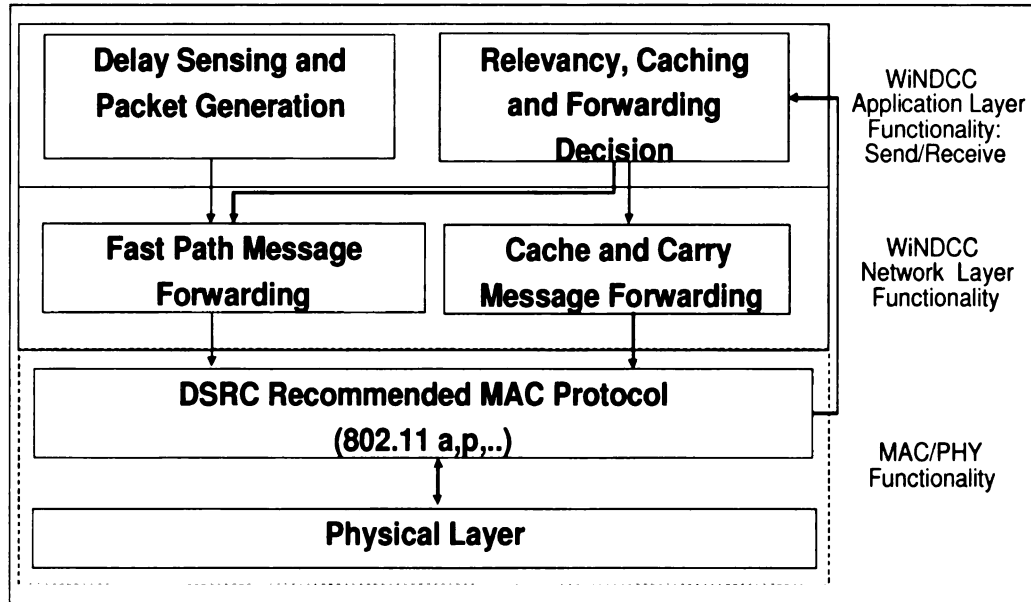


Figure 3-3: WiNDCC network architecture

With regard to the traditional networking architecture used when describing wireless systems, WiNDCC operation can also be discussed in this way. Figure 3-3 depicts this architecture. By viewing it, one realizes the research contributions made in this thesis. From an application layer perspective, the primary purposes are to generate delay messages and determine what to do when delay messages are received. The details of these actions will be described in this chapter. At the network or routing layer, the two forwarding mechanisms can be seen. The details of the two will be covered next, along with an explanation of when they are used. However, as mentioned within the WiNDCC problem specification, the fast forwarding specification is based upon [22], and the *cache and carry* paradigm upon ideals from [27]. Additionally, note that when nodes receive information from the MAC layer it is relayed directly to the application layer. That is, in the WiNDCC system the network layer serves the application layer, not the other way around. This is a result of the broadcast nature of system operation. Also in the

WiNDCC specification presented in this thesis, the IEEE and ASTM-adopted Dedicated Short Range Communication (DSRC) recommended MAC layer protocol is used.

3.2.3 Architectural Summary

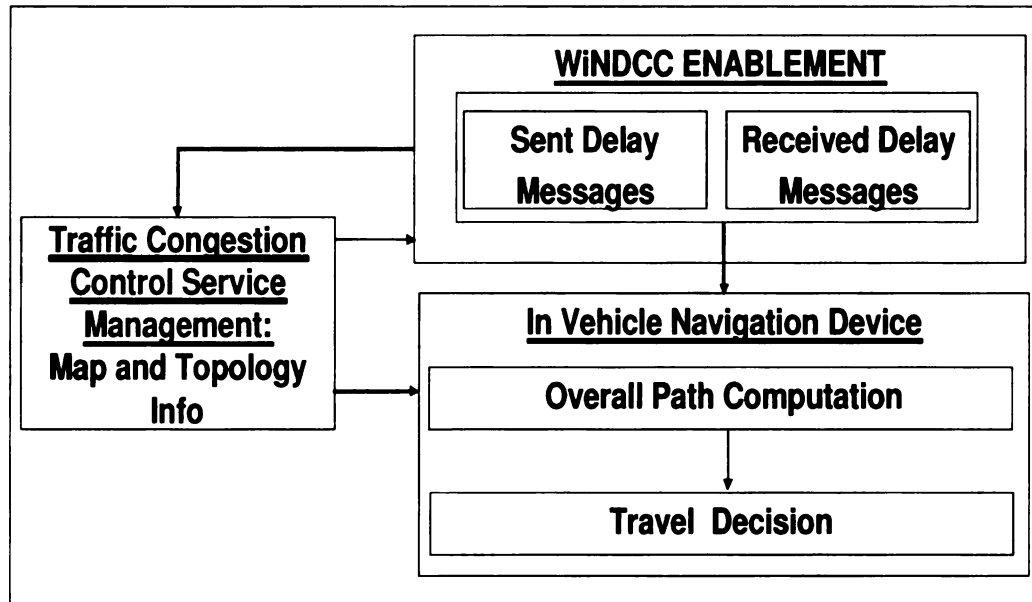


Figure 3-4: Overall system architectural summary

In summary, the overall system operation can be seen in Figure 3-4. In short, the service management layer provides mapping information to WiNDCC and the navigation device. In addition, WiNDCC supplies the information sensed from other enabled vehicles to the navigation device, which then calculates the travel route based on this information. WiNDCC is also responsible for sensing and relaying the information it knows about the traffic network. Finally, the navigation entity outputs the next travel decision to the driver based on the route it has calculated. To be examined as future work, the WiNDCC system can also provide information to the service manager, for the purpose of enhanced traffic monitoring and control.

3.3 WiNDCC Operational Assumption

In order for WiNDCC to operate under the premises described in this thesis, a few assumptions or system inputs are needed. Firstly, as with all navigational and route

computation devices, the position of the equipped vehicle is vital to system operation and performance. WiNDCC also uses position data for not only for route computation but for overall protocol functionality as well. For instance, the system constantly measures a vehicle's current time spent in a link. Therefore, it is imperative that the system be able to stamp the appropriate time in which a vehicle has entered a link. This sort of functionality, along with a few other mechanism nuances, depends heavily on accurate position data. As a consequence, for the remainder of this document, assume that enabled vehicles are always position aware.

3.4 Path Computation Function

In the abovementioned system breakdown, it can be seen that the navigation device or function is responsible for using the initial and learned information about the traffic network to supply the travel decisions to drivers. In the WiNDCC system presented in this thesis, the travel routes are computed using the following rationale.

With respect to the way in which vehicular navigation and route guidance systems acquire the actual travel routes reported to users, a shortest path algorithm is equipped. Particular to the mechanisms and system specifications for WiNDCC, the Dijkstra's shortest path algorithm is constantly invoked throughout travel to compute the guidance messages reported to drivers. In order to use the algorithm according to the WiNDCC mechanism, the traffic network first needs to be represented in graphical form, by representing intersections as vertices, or nodes, and roadways as links, or edges. Link costs are also utilized in order to judge the quality, effectiveness, or any other designer specified quantity associated with links. The link costs associated with WiNDCC are the travel times associated with each link. Initially, they are set to the optimal or free flow

travel times, so that vehicles always use these paths when no other knowledge has been obtained about travel links. As a consequence, the broadcast and received delay messages will pertain to the travel times of the vehicles sending them. Nevertheless, these details will be discussed in the next section. With respect to other required inputs to the algorithm, the source or current position of a vehicle is required, along with the intended destination; however in regard to general algorithm specifications, a destination is not required as the original algorithm computes routes to each graphical destination. As a consequence, based on the indicated inputs, the algorithm provides a directed graph as output that corresponds to the shortest paths associated with the traffic network. Here [32], the authors present the Dijkstra's algorithm, along with another search technique called bidirectional A*, which will not be used in this work. However, the work does discuss and analyze the ability to use the Dijkstra's algorithm within vehicular navigation contexts to find all paths between a source and destination. It can be seen that Dijkstra's is effectively able to compute the various paths within the road network.

**Path Computation Procedure at Navigation/WiNDCC enabled node - i,
pertaining to traffic topology T:**

```
While(Vehicle i has not reached destination)
//Create directed graph G, in which Dijkstra's algorithm will use to compute
//shortest path tree S (G is restricted such that u-turns are eliminated from
//next hop consideration)
For(Every link, j, in T)
    If(Vehicle i has an Updated Delay Value (UDV) for j){
        Vehicle i will place link j into G using UDV
    }Else{
        Vehicle i will place link j into G using Typical Delay
        Value (TDV)
    }
//Run Dijkstra's algorithm on G, given current position and destination, to
//compute S
//Vehicular navigation device associated with i will then determine its next
//travel decision based on S, its current position within T and the desired
//destination
```

Figure 3-5: Path computation module

In terms of the algorithmic description of the path computation process, Figure 3-5 is given. In it, the Typical Delay Values (TDV) are the delay values for any link under optimal travel conditions, and Updated Delay values (UDV) are those learned from other WiNDCC enabled devices. Therefore, if there is not any learned information about the traffic topology, vehicles will use the theoretical best path.

3.5 WiNDCC Packet Contents

| | | | |
|-----------------------------|------------------------------|----------------------------|----------------------|
| Reporting Back Intersection | Reporting Front Intersection | Reporting X Position | Reporting Y Position |
| Senders Back Intersection | Senders Front Intersection | Senders X Position | Senders Y Position |
| Delay Time | Time Stamp | Cache and Carry Identifier | |

Table 3-1: WiNDCC packet contents

The packets exchanged for WiNDCC operation are very simple in nature and will be described in this section. In terms of the information that is needed for system operation, it can be found within the packet contents. For a visual perspective of the packet contents, examine Table 3-1.

To begin with, the first row of content deals with the positioning of the link being reported by the packet. The reporting back and front fields combine to represent the road in which the packet describes; while the reporting x and y designate the exact position of the vehicle when reporting this data. The second row pertains to the same information, but relating to the node sending the packet. In a subsequent section that describes message forwarding, it will be seen the purpose of including this information within WiNDCC packets. Nevertheless, these two rows of information will be the same, when considering the packets being generated by nodes originating protocol messages. However when the packet is being forwarded, the sender information is replaced by that of the node forwarding the packet, corresponding to the reporting information. Finally, the last row of data includes the actual delay information relating to the road segment, which is identified in row one. In terms of the individual components, the delay time

field contains the delay value for the segment, and the time stamp equates to the moment of time the extraction takes place. To be explained in the forwarding principles section, the background identifier is a Boolean piece of data, which indicates the forwarding status of a message.

By examining the abovementioned packet contents, some WiNDCC characteristics can be noticed outright. To begin with, there is not any indication of which node has originated the data packet, beyond the position data included in the first row. This is because the WiNDCC system operates via a broadcast dissemination scheme, where the originator of protocol information is negligible compared to the actual information itself. Additionally, there is no destination information included in the header. However, it will be seen in the forwarding section the traffic network regions in which packets are destined within the WiNDCC framework. Therefore to understand the purpose of WiNDCC packet data, consider the remaining system specification and description.

3.6 Delay Message Generation

In this section, details will be given pertaining to the way in which WiNDCC enabled vehicular devices will generate the delay messages to be broadcast around the network. With respect to this task, there are two operational modes. The first operational mode works during times when travel links are congested, not completely stopped. The second comes into play when links are stopped due to accidents or other traffic events. Nevertheless, no matter the operational mode, a vehicle will only generate delay messages about the link it is currently residing. That is, vehicles will not generate delay messages about other links in the traffic topology. However, it is an acceptable part of

system operation for vehicles to forward messages about other links. This will be described in the message forwarding sub section of this chapter.

3.6.1 Message Generation Based on Initial Congestion Indicator

$$RCI = \frac{(Time_spent_in_link - Typical_Delay_Value)}{Typical_Delay_Value}$$

Figure 3-6: Calculation of RCI

During times when links are moving but could possibly be displaying congested conditions, WiNDCC uses an Initial Congestion Indicator (ICI) to determine if congestion is present. In other words, the ICI helps the system determine a definition for congestion. Additionally, this definition is adjustable and can be a function of time or other system aspects, according to the specifications set forth by system management. Generally speaking, the ICI and Relative Congestion Index (RCI) are compared to determine when it is appropriate to begin broadcasting information about a road link. To clarify, the RCI is a vehicles current time spent in a link, relative to the free flow travel time or TDV described in the original path computation procedure. By utilizing this quantity, a snapshot of the delay characteristic of a link can be gathered. The RCI computation is found in Figure 3-6. As a consequence, the comparison of RCI and ICI allows system operators to determine how much traffic congestion to accept before broadcasting messages via WiNDCC, which could potentially begin to redirect traffic. That is, when the RCI is greater than the ICI, the condition for declaring traffic congestion has been met. However, until this criterion has been met, it is unnecessary to broadcast information about a link and the channel should remain clear. This concept supports vehicles using the optimal paths when congestion is not present or is not above the threshold determined by the ICI. For this study the ICI is the same for each link in the entire traffic network. However in a study left for future work, it may prove to be

advantageous to attach various ICI values on a per link basis, to assist with meeting network wide traffic goals determined by service management.

Now that the ICI concept has been discussed, it is now appropriate to describe when the actual link delay times will be broadcast. As prescribed in [21, 29], an effective strategy when implementing a dynamic route guidance system is to use the delay times experienced by vehicles when they exit travel links, as link costs or references in route computation. As a consequence and since the system uses actual or typical delay values to compute routes, WiNDCC borrows this concept and has vehicles broadcast delay information as they exit links; That is, during times of congestion or slowed links, vehicles broadcast the delay it has experienced in that travel link. Additionally, other logic is introduced to assist in minimizing the wireless channel usage and to assist in delay notification and smoothing.

Link Exit Procedure at WiNDCC enabled node - i, exiting Road Link-l:

```
//Vehicle i determines the total time it has spent in link l: tot_time

//By using tot_time and typical delay value for link l (TDV), vehicle i
//computes relative congestion index (RCI - Figure 3-6 )

If(Vehicle i does not have an Updated Delay Value (UDV) for link l){

    If(RCI is greater than Initial Congestion Identifier (ICI) ){

        Vehicle i Sends Delay Packet about link l, indicating the tot_time.

        Set UDV to tot_time

        Return;                                     }

    }Else                                           {

        If(The vehicle i has received a delay message about l in last 20 seconds){

            Return;                                     }

            tdiff = tot_time – UDV    //Determine difference between
                                     //tot_time and UDV

            If(tdiff < 0){        //Congestion could be improving

                If(abs(tdiff)<20){

                    Return;        //Not as sure if congestion improving

                }

            }

        }

    }

}
```

Figure 3-7: Link exit strategy

Link Exit Procedure at WiNDCC enabled node - i, exiting Road Link-l:

(Continued)

Vehicle i Sends Delay Packet about link l, indicating the tot_time.

Set UDV to tot_time

Exit

Figure 3-8: Link exit strategy (continued)

As a reference, the link exit broadcast strategy is described in Figure 3-7 and Figure 3-8. As previously mentioned, the ICI dictates when the broadcasting will begin or cease for a certain link. As a consequence, the algorithm exits if the RCI is not greater than the ICI and the vehicle invoking the exit strategy has not already received an update for the link. Then in instances when updates have been received, efforts are made to keep the wireless channel free and minimally used, while also keeping the delay information fresh within the network. To achieve this, a guard time is applied that disallows multiple information originations within that time, in this case 20 seconds. That is, during times of increasing congestion, messages will be generated no less than 20 seconds apart. Also, delay broadcasts for values lower than those currently cached within a node will be filtered. This is done to be sure the delay time is being adequately decreased about the link, before broadcasting it. That is, to smooth the data as congestion is potentially being relieved in a link, the reduced delay value must be at least 20 seconds less than the current one being used in route computation in order to be broadcast. If not, the routine exits and a message is not sent.

3.6.2 Delay Message Generation during Times of Event

Event Notification Procedure at WiNDCC enabled node - i, residing in Road

Link-l:

```
//Vehicle i determines the total time it has spent in link l: tot_time

//EWT set based on delay reception about l or entry time into l

    If(Vehcile i has not heard a delay message in EWT or has not exited l){

        If(EWT has expired){

            Set Event Backoff Timer (EBT)

                }

            //*****EBT has expired

            If(Vehicle i has not heard a delay message about l){

                //Vehicle i Sends Delay Packet about link l, indicating the tot_time

                //every 20 seconds until it or another vehicle or itself moves out of l.

                UDV = tot_time                                }

            }

        }
```

Figure 3-9: Event notification procedure

When links are stopped due to traffic collision, a vehicle malfunctioning on the road, or any other unforeseen traffic event, WiNDCC instructs a vehicle near the event region to send protocol messages, notifying the network of stopped traffic flow. The logic for such activity is found in Figure 3-9.

In this procedure each stopped WiNDCC enabled node waits a predetermined amount of time, in reference to the time when it has entered the link or received the last

delay message about it, before broadcasting any information. This is to be sure that an event is taking place and that the link is not slowed but still moving. That is, the Event Wait Time (EWT) is equal to the sum of the TDV of the link in question and the smallest of the TDV values for the other links using the intersection, traveling in a perpendicular direction. For example, if a vehicle is stopped in a link that is travelling north, its WiNDCC enablement will wait a time period equal to the sum of the TDV for the lane it is residing and the shorter TDV of the lanes traveling east and west into the intersection it is using. Then, if a node in the lane hears a delay message about the link within this time period, it stops waiting and will not send any delay messages about the link. In this case, either the link is still moving or another vehicle has controlled the broadcast channel for the purpose of event notification. If the latter is the case, this vehicle will dominate the broadcast channel and deliver all messages about this event until it exits the link.

As previously mentioned, a vehicle will either wait for the EWT in reference to the time when it has entered the link or, if it has received a delay notification about the road in question, the time it has received the most recent delay message about the link. In both cases and in terms of the event broadcast scheme in general, the most important aspect of this notification is ensuring that an event has actually taken place and that only one vehicle controls the broadcast channel. Therefore, as it can be seen in the algorithmic description, a shorter wait time is applied after the EWT. This timer guarantees, especially in the case of a group of vehicles who have received a delay message at the same time and are waiting to broadcast an event message after waiting the EWT, that only one vehicle sends information. That is, the Event Backoff Time (EBT) is simply the reciprocal of a vehicle's current distance from the previous intersection or back of the

link. By applying this time, the mechanism pledges to only allow one vehicle to report the event that is happening. And as a consequence of the distance basis for this timer, vehicles towards the front of the event area are favored for event notification.

Finally, it can be seen that the event message is re-sent by the EWT and EBT designated vehicle every 20 seconds, with the updated amount of time this vehicle has spent in the link. This is done to keep other vehicles from commenting on the status of the link in question and to refresh the traffic information around the network, while not clogging the wireless channel in an effort to do so. Once a vehicle exits a link and updates the information for the link at hand, the event notification status ceases.

3.7 WiNDCC Message Forwarding Algorithms

In the previous section, the delay message generation schemes utilized within the WiNDCC system specification were discussed. Briefly stated, the framework generates delay messages under two circumstances. The first classification is link exit, and the second is during times of events. Also, it can be seen in their algorithmic descriptions that attempts are made to maintain the health of the wireless channel while introducing fresh information within the traffic network. Similarly, the WiNDCC forwarding procedures are designed with the same principles in mind, forwarding fresh information and doing so in a manner that uses the wireless communication channel effectively. In the following sections, those schemes are introduced and described to the reader.

3.7.1 Relevant Areas for Message Forwarding

According to the established design principles, WiNDCC is a completely distributed, infrastructure free, traffic delay mitigation mechanism; therefore it is very

important, for wireless channel and overall mechanism competence, to forward messages in an efficient manner. Obviously, an important aspect of reliable forwarding is the forwarding scheme itself. However, an equally important question in relation to this task is where within the traffic network the messages are being forwarded. That is, when delay messages are generated, it is in the best interest of the wireless channel and system goals for them to be forwarded to the areas of the traffic topology that can use them, not to areas that the information is irrelevant. The discussion about WiNDCC message forwarding will begin with this idea in mind, with a description of geographic information relevancy. Additionally, in [25] two definitions are introduced that relate to describing this situation. The first is zone of relevance (ZOR), which is the set of geographic criteria a node must satisfy in order for a message to be relevant to it; the second is zone of forwarding (ZOF), which is the set of geographic criteria a node must satisfy in order to forward a message. One will find various mentioning of these terms within the forwarding description.

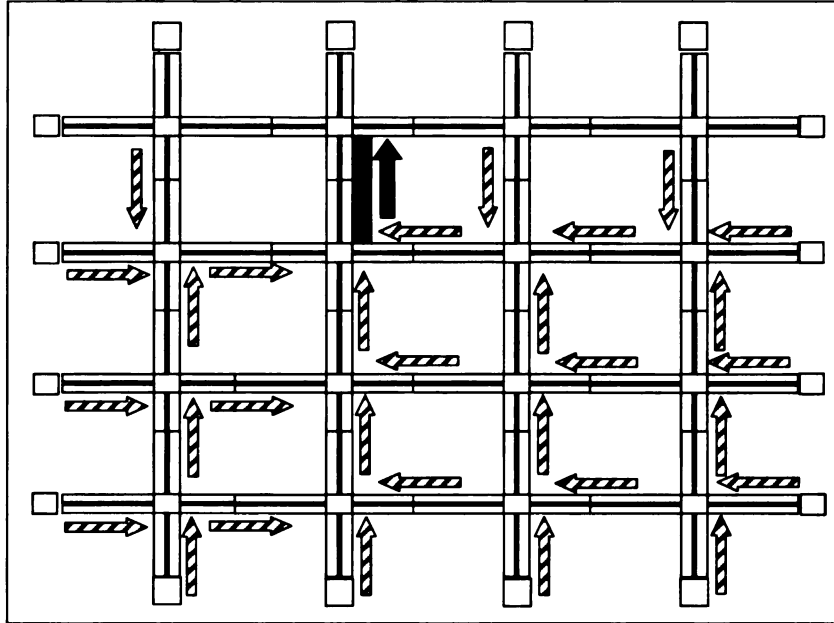


Figure 3-10: ZOR for info from darkened link, marked with stripes

Considering the message generation paradigm, discussed in the abovementioned sections for link exit or event notification, the generated information is relevant to a particular area within the traffic environment. That is, the ZOR is a defined set of links, as it relates to the messages generated by nodes in a particular roadway within the topology. Simply stated, the relevant links are those that could potentially be input for the link in question. For an example, consider Figure 3-10 and delay messages originated from the darkened incident link. According to the WiNDCC paradigm, and intuitive driving logic, the links marked with stripes are potential input roads for the darkened link and vehicles using them would need the information about this link. Also according to intuitive driving logic, the links closest to the darkened one would need the information before the ones farther away. A verbal definition, of the ZOR for messages originating from a particular link, is as follows. That is, the ZOR for a roadway includes all roads parallel to the one in question, but opposite in direction, and each link that serves as

eventual input to it. To be examined as future work and particular to an individual road network, the depth or distance from the incident link associated with a ZOR should be determined particular to the topology in question. It will be shown in the next section how the ZOR associated with links within the WiNDCC framework is used within the forwarding mechanism.

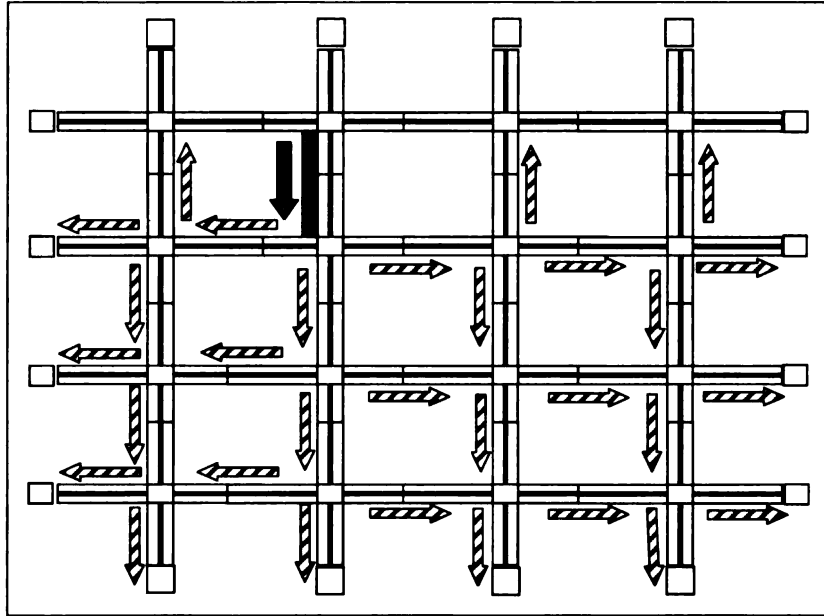


Figure 3-11: ZOR for info from striped links, darkened

Also, considered within the WiNDCC framework is the question of what information is relevant to a traveling vehicle. Contrary to the previous issue, this one deals with information about the potential links a vehicle may travel, not the roads that serve as input to an exact one. Simply stated, the problem and solution are an inversion of the one mentioned earlier and the following statements are made with respect to this new vantage point. Therefore, the ZOR is a single link, as opposed to the previous case where the ZOR was a group of links. And, the incident area is considered to be a group of links, the prospective roadways a vehicle may use. For a visual aid, consider Figure 3-11. For a vehicle traveling in the darkened link, the messages generated about the striped links are relevant. A verbal definition, for the incident area according to particular link, is as follows. That is, the incident area for a roadway includes all roads parallel to the one in question, but opposite in direction, and each link that serves as eventual output from it. Additionally, to be examined as future work, the size or distance associated with

the incident area will be left as future work and is particular to the traffic network topology at hand.

The ideas presented in this section are important, in terms of the WiNDCC forwarding operations. It will be revealed in the next section the role of information relevancy within this framework. As an additional note, the information has been presented in this order to assist the reader in understanding the schematics.

3.7.2 Receive Module: Forwarding Decision

An appropriate place, to begin describing the interworking of the WiNDCC forwarding module, is at the receive module. By reexamining the wireless networking architecture found in Figure 3-3, one can see that the receive module makes a decision about the forwarding status of a packet. When considering the nature of WiNDCC operation, it is clear why this is so. That is, the only time a device will forward a piece of information is if it receives it from another node, via the broadcast communication channel equipped for this framework. The receive module will be explained here, while the details of the forwarding modules themselves will be left for the next sections.

Receive/Forward Decision Module at WiNDCC enabled node - i, residing in

Road Link-l:

```
//Receive delay packet from MAC layer about link j: packet
//Be sure information is fresher than that cached for l
//Record all relevant information from packet
//Set Data Expiration Time
If(link l is within the ZOR for j)or(l and j are the same){
//Mark packet for fast path forwarding
Fast_Path_Forward(packet)
}else{
//Mark packet as cache and carry packet
Cache_and_Carry_Forward(packet)
}
//After this, a packet has been labeled as background
If(Packet is labeled as a background packet){
//Cancel current forwarding choice
Cache_and_Carry_Forward(packet)
}
```

Figure 3-12: Logic for receive module

$$\text{Data_Expiration_Time} = \text{Time_Stamp} + 2 * (\text{Delay_Time} + \text{RCI_for_packet} * \text{Delay_Time})$$

Figure 3-13: DET computation

The receive module logic can be plainly explained, when considering the ideas presented within the WiNDCC general algorithmic description and the previous section, 3.7.1. An algorithmic perspective for it can be found in Figure 3-12. First, if the received information is fresher than what the node already has for the indicated link, then the procedure logs the relevant information found within the packet and determines the Data Expiration Time (DET). The DET is a quantity describing how long it is permissible for a device to forward or use a piece of data in route computation. It is based upon the reported delay value, the time stamp for which the data was recorded, and the TDV for the link. That is, the TDV and the recorded delay value are used to compute an RCI and DET for the message. In essence, the term is designed such that information from packets reporting a high RCI remains in the network longer. Its computation can be found in Figure 3-13.

Then, if a vehicle is within the ZOR for a protocol message about a link, it marks this packet for the fast path message forwarding procedure found within the routing layer of the network architecture. It will also perform this operation if the receiving vehicle resides within the link in which the message is generated. That is, in reference to the scenario depicted in Figure 3-10, a vehicle inside of any highlighted roadways will mark a packet for the fast path message forwarding mechanism, if it is generated within the darkened link. Otherwise, if a vehicle that is not inside the ZOR receives the packet, the data is marked as *cache and carry*; now, the corresponding forwarding principles are ready to be invoked. Additionally, logic is found within the receive module for the reception of a *cache and carry* packet, which will be explained later.

Although simple in nature, the receive module plays an important role in WiNDCC. Next, the forwarding modules that combine to create the WiNDCC network layer will be discussed.

3.7.3 Fast Path Message Forwarding

$$Forward_Attempt_Time = \frac{(25)}{Distance_From_Sender} \text{ Seconds}$$

Figure 3-14: FAT definition

The purpose of the fast path message forwarding paradigm is straightforward and is as follows. Namely, the mechanism aims to get the information to the ZOR for the reported link as fast as possible, while maintaining as much integrity as possible over the wireless channel. Therefore as previously mentioned in the related works section, an idea from the mechanism described in [22] is used to assist in this process. In short, the mechanism uses a distance based backoff scheme that expeditiously moves messages as away from an origination node. This is done by applying the distance based backoff time of Figure 2-1, upon packet reception. As a consequence, that gives vehicular devices farther away from the sending node forwarding priority. Then by taking advantage of the broadcast medium in which all nodes in radio range of a transmission hear it, other vehicles waiting to forward this message cancel this operation. Therefore, as a function of the underlying network topology, this allows messages to move as far away as possible while minimizing the amount of wireless transmissions.

WiNDCC combines this concept with the ZOR to create the backbone of its fast forwarding function. However, the Forward Attempt Time (FAT) used for this mechanism is different from the one shown in Figure 2-1, but it serves the same purpose. The FAT definition is found in Figure 3-14 and it uses the sender information described in the packet contents, section 3.5. By viewing it, one can see that vehicles closer to the

sender wait a longer time to forward packets, as described in [22]. This promotes the overall goal of fast path message forwarding, to move messages far away fast.

Fast Forwarding Module at WiNDCC enabled node – i:

//Packet has already been identified and passed into the function

//Set FAT

If (FAT has expired before hearing message reply){

Forward_Packet()

}

Figure 3-15: Fast forwarding logic

The fast path message forwarding scheme is described in Figure 3-15. In summary, anytime a vehicle receives a packet for which it is among the ZOR and the fast path forwarding routine is invoked, the FAT is set and the vehicle waits to hear a reply for the message. Then, if it does not hear a reply before the FAT expires, it forwards the delay notification reply. To conclude the fast forwarding process, when a vehicle sends a reply message and does not hear it rebroadcast from another node within 5 seconds, the fast forwarding for that packet stops and the network is said to be partitioned in that geographical area. 5 seconds is used because it describes the longest forward time allowed by the FAT, assuming vehicles stop around 6 meters from one another. By utilizing this principle, a message is able to traverse as many of the striped links in Figure 3-10 as possible, until the network is partitioned. Two schemes used to counter the effects of a partitioned vehicular network are shown in the final sections of this chapter.

3.7.4 Fast Path Message Forwarding with Partition Bridging

To deal with partitioning within the traffic network, the fast forwarding algorithm may be used in a mode offering partition bridging. This mode is very simple and will be described in this section.

As a basis for this algorithmic nuance, [29] is referenced and the dissemination interval from it is used, Figure 2-2. In WiNDCC, this term will be called the Adaptive Dissemination Interval (ADI). Given R , k , v_1 , and v_2 as described within the term definition, a WiNDCC enabled vehicle can calculate the maximum transmission interval needed to inform passing vehicles of any information it has. This term is used in the partition bridging addition to the fast path message forwarding algorithm in the following manner. That is, for a vehicle that has not heard a retransmission of a reply message it has sent, it rebroadcasts it at an interval less than the ADI to try and bridge the partition in the network. In terms of the ADI computation, the quantity $v_1 + v_2$ is equal to the sum of the forwarding vehicles velocity and the speed limit of the roadway in the opposite direction. This is because WiNDCC does not exchange velocity information. Therefore, a node has no knowledge of the velocity in the opposite direction; so it uses the speed limit for that link. Upon reception by a vehicle within the link of the forwarding vehicle or the ZOR for the forwarded message, the fast forwarding algorithm is then invoked by the receiving node. That is, the previously discussed receive module logic is adhered to.

When this mechanism is used, a packet will live in the network as long as the DET constraint is valid. As a consequence, the partition bridging allows a packet to move as far as possible, by forwarding it at the edge of a partition until it hears a reply that it has been received by another device.

3.7.5 *Cache and Carry* Message Forwarding

The final subcomponent of the WiNDCC network layer is the *cache and carry* forwarding mechanism. As was mentioned within the related work section, several VANET oriented routing mechanisms sometimes use a *cache and carry*, or store and forward, approach to forwarding packets [26-28]. Like those works, WiNDCC also incorporates a store and forward methodology to forwarding packet. As previously mentioned, the purpose of this activity within the WiNDCC framework is to assist in areas where the traffic network is partitioned, and messages are unable to effectively traverse the network beyond this point of partitioning by way of the fast forwarding method. The most effective way, to begin describing the operation of the *cache and carry* paradigm, is by reexamining the above mentioned discussion about information relevancy.

By reconsidering the receive module logic, it can be seen that when a message is generated or forwarded about a certain link and a receiving vehicle is not within the ZOR for the reported link, the function marks the packet for *cache and carry*; then it calls the routine. Simply stated, the *cache and carry* mechanism will rebroadcast certain cached information, according to its current position within the topology. The rebroadcasted information is intended for vehicles traveling in links that are traveling in the opposite direction and are using the intersection that is directly in the rear of the broadcasting vehicle.

By viewing Figure 3-11, the abovementioned concepts and the overall operation of the *cache and carry* algorithm can be understood. Consider the darkened and any vehicle traveling within it. As previously mentioned, the information about the striped links is

relevant to this vehicle, because they are the potential links the vehicle could travel. An additional nuance of this scenario is as follows; it can be seen that the darkened link is within the ZOR for each of the striped links. However due to the partitioning within the network, information may not make it from the striped links to the darkened one; although, this information could be useful to any of the traveling vehicles using the darkened roadway. As a consequence and according to the pictured example, the *cache and carry* procedure instructs vehicles to broadcast the *cache and carry* information they have learned about the striped links, when they are in the link beside the darkened one.

**Cache and Carry Forwarding Module at WiNDCC enabled node – i,
entering link j:**

```
//Determine cached information regarding potential incident links for the road  
//traveling in the opposite direction  
  
//Set randomized start time for each potential piece of data  
  
If(DET for a broadcasted message has not expired)or(i has not received  
fresher info about a link being broadcast){  
  
//Broadcast potential incident link information every ADI  
  
}
```

Figure 3-16: *Cache and carry functionality*

The details of this procedure are outlined in Figure 3-16. In specific, at the moment a vehicle enters a new link, it calls the *cache and carry* function to determine if it has any relevant information stored that could be of use to a vehicle using the lane opposite of it. In the event that it does, a random timer is for each piece of data the vehicle may broadcast. This random value is selected such that the vehicle is able to move away from the intersection before broadcasting information, so that the communication channel can remain as clear as possible for the link exit delay generation activities. Then, until the DET expires for the data or fresher information about the information is received, then the information is broadcast according to the ADI.

Chapter 4: Experimental Setup

In this chapter, a discussion of the simulation setup is given. Performance of WiNDCC was evaluated using the ns-2 network simulator version 2.30. In terms of its high level operation, Ns-2 is an event-driven C++ and TCL language based network simulator. Particular to its usage within industrial and research realms, it is open source and can be extended to implement many wired and wireless network protocols and scenarios. Additionally, the simulator comes with various components pre installed. Currently ns-2 does not support vehicular or traffic network oriented simulation environments; therefore, a macro vehicular simulator was designed and implemented using ns-2 to support the type of experiments depicted in this thesis. Also in this chapter, other aspects of the experimental setup are discussed.

4.1 Macro Vehicular Simulator

Here, a description will be given of the macro vehicular simulator used as a testbed for the WiNDCC system. To clarify, the term macro is used because the simulator is not intended to measure the low level interaction between vehicles. Instead, the design is meant to measure the overall movement of vehicles and track the end to end and per link travel delay associated with the simulated nodes. Also according to the macro mobility nature of the simulator, vehicles are able to stop and accelerate instantaneously. Nevertheless, in an effort to gain a perspective on WiNDCC algorithmic relevance and performance, the traffic network implemented by the simulator has roadways with one lane of travel in each direction and implements traffic light logic at intersections. As

future work, WiNDCC should be analyzed with a more realistic vehicular simulator. However, to gather preliminary results, the macro vehicular simulator serves its purpose.

In terms of the workload and time required to complete this thesis, the macro vehicular simulator design, implementation, and intense debugging constituted a majority of the initial effort. Nevertheless, in order to begin development and testing of the WiNDCC system, a way to test its effectiveness had to be obtained. As a consequence, a large portion of the macro vehicular simulator was developed before the start of WiNDCC design.

Particular to the vehicular simulator design, a few components are responsible for its implementation; some of them are already built into the ns-2 network simulator. In terms of the programming language and ns-2 usage in general, most exterior and pre installed components are written in C++. However, the TCL scripting language is involved with inputting initial simulator state at runtime, allowing interaction between unrelated simulator objects, low layer simulator functionality. Nevertheless, the system description is as follows.

4.1.1 Pre-installed Ns-2 Dependencies

In ns-2, there are functions that can be called to control nodal movements within the simulated environment. In terms of the macro vehicular simulator operation, these functions are at the core of its functionality and are used to make the nodes or vehicles move. The functions are a component of the ns-2 preinstalled mobilenode object. Also, anything dealing with the position or velocity of a node is enabled by invoking its mobilenode routines. It will be seen in the following descriptions the usage of mobilenode routines.

Especially characteristic to network protocols, timing is a critical component of mechanism design and operation. As a consequence, ns-2 uses timers to allow protocol designers a way to schedule events during the simulation time. In terms of usage, a timer is a function that allows the designer to specify when it will expire and the corresponding code that will be ran at this time. Depending on the application or simulation operation, a programmer can vary the expiration time as well as disable the timer. As with traditional networking protocols, the macro vehicular simulator and WiNDCC implementation is highly dependant on the ns-2 timer capabilities.

4.1.2 Input Simulation Script

Here, insight will be given as to the inputs for traffic simulation via the macro vehicular simulator. Since the macro vehicular simulator implements vehicles traveling within a specific traffic network topology, the physical characteristics of the roadway network must be first inputted into the simulation space so that each vehicle can be aware of it. Along with the intersections in which they are connected, the x and y coordinates of all simulated links are fed into the simulation space with the input or configuration script. As a consequence, the graphical representation of the traffic topology, to be used within the vehicular route computation module, is obtained. Additionally, the speed limit and length of the segments are given to complete the traffic road link topology input.

In addition, the traffic light information is given in the configuration script. In accordance with the type of traffic lights used within the experimental setup, lights are green, yellow, or red. The timing for each traffic light state is given as well as the simulation time in which the traffic light will begin to operate. Of course, the logic for this device is the same as what is seen in actual stoplight implementations. That is, the

light goes from yellow to red, then from red to green. The process continuously repeats itself, according to the timer specifications which enable it.

Finally, the information about each simulated vehicle is provided in the initial simulation script. This information includes the x and y position of the node and other simulator and WiNDCC specific variable initiations. Also the type of traffic decision module the vehicle will use is set. The options for this model are random, best path, and WiNDCC assisted. The random module instructs a vehicle to make a random decision at each traffic light; a best path vehicle always uses the theoretical best path for travel, and the WiNDCC assisted vehicles use the logic described for WiNDCC. For the last two cases, the destination is also set for a vehicle. Lastly, the start time for a vehicle is prescribed as input.

4.1.3 Topology Interaction and Position Awareness

In terms of a vehicle traveling within the simulation environment, it must react and be aware of the topology. This functionality is implemented by three timers residing within each vehicle.

The first timer is the position awareness and intersection behavior function. For each node, this timer expires rapidly during the simulation time. This is so that vehicles always have an accurate understanding of their position. As will be seen in the next section, the sanity of other modules also depends on the vehicle having an accurate understanding of its position at all times. Also, according to the WiNDCC application and network layer goals, position information is vital to system operation. In addition, this function also calls the mobilenode routines that move the node when a node enters

and exits an intersection. It also, upon entry into a new link, sets the state variables needed for simulator operation and WiNDCC functionality.

Another timer assisting with topology interaction allows vehicles to be aware of the state of traffic lights as they approach them. For the vehicle in the front of a lane, the traffic light timer instructs this vehicle to periodically get the light status from the traffic light object serving it. Also, included within the traffic light timer are instructions about where and when to stop due to the traffic light state.

Finally, as mentioned in section 3.4, WiNDCC uses the Dijkstra's shortest path algorithm to compute travel paths. This module interacts with the topology by using the inputted road link profile. This profile, along with the current position and destination of the node, is used by the described route computation module to dictate a vehicles travel decisions. If WiNDCC is enabled, then the information learned about the traffic topology can also be used as input to this process. If not and a vehicle is a best path traveler, the theoretical travel times are used.

4.1.4 Vehicular Interaction

The last module responsible for the macro vehicular simulator operation is the vehicle reaction timer. In specific, this timer is responsible for vehicle to vehicle interaction. Like the position awareness timer, this timer expires constantly and uses the position of not only the vehicle calling the function but the position of the vehicle immediately in front of it. The function instructs a vehicle of when and where to stop due to a stopped leading vehicle, and it also tells the vehicle when to proceed after the leading vehicle resumes travel. In addition, the module also adjusts a vehicles traveling velocity

according to that of the front vehicle. This module is important to guaranteeing vehicular sanity throughout the simulation process.

4.2 WiNDCC Implementation

According to the specifications set forth in chapter 3, each aspect of the WiNDCC system is implemented within the simulated vehicles. The system uses a built in ns-2 module called the pingagent. This skeleton object is simply equipped with a send and receive module that allows interaction with the specified MAC layer. Most designers use this space for protocol development on the ns-2 system. According to the WiNDCC design principles, both network and application layer functionality is implemented in this object. As previously mentioned, several timers, c++ functions, and TCL backbone interaction calls are used to implement the system. The algorithms have been described in chapter 3 and are tested for effectiveness in the following chapters.

4.3 External Components

With regard to the results that will be presented in the following chapters, the act of getting them into a usable form was as important as the actual results themselves. That is, within the macro vehicular simulator and WiNDCC implementation code, there are several cout statements that allow the designer to understand what and when certain events are happening within the simulation time. These output statements are analyzed to produce the results. However before they can be understood, the trace file that contains all of the generated output statements produced within the simulation must be parsed and put into a format that is conducive to plotting. Due to the extreme amount of data presented during each simulation run, this was a very important aspect of the end to end

process associated with simulator design and experimental evaluation. To perform this task, several scripts were written and used. The involved languages were awk and sed, along with additional shell scripts used to creatively call the various programs. By using the two scripting paradigms, routines were created that were responsible for identifying, extracting, and tabulating each performance metric. In summary, the external scripting components are vital to gathering the performance metrics the reader will see.

4.4 Commonalities between Experimental Scenarios

Here, some insight will be given into the experimental scenarios that will be described in the following chapters. The settings and characteristics that are shared between each experimental setup are found below.

4.4.1 Experimental Topology and Characteristics

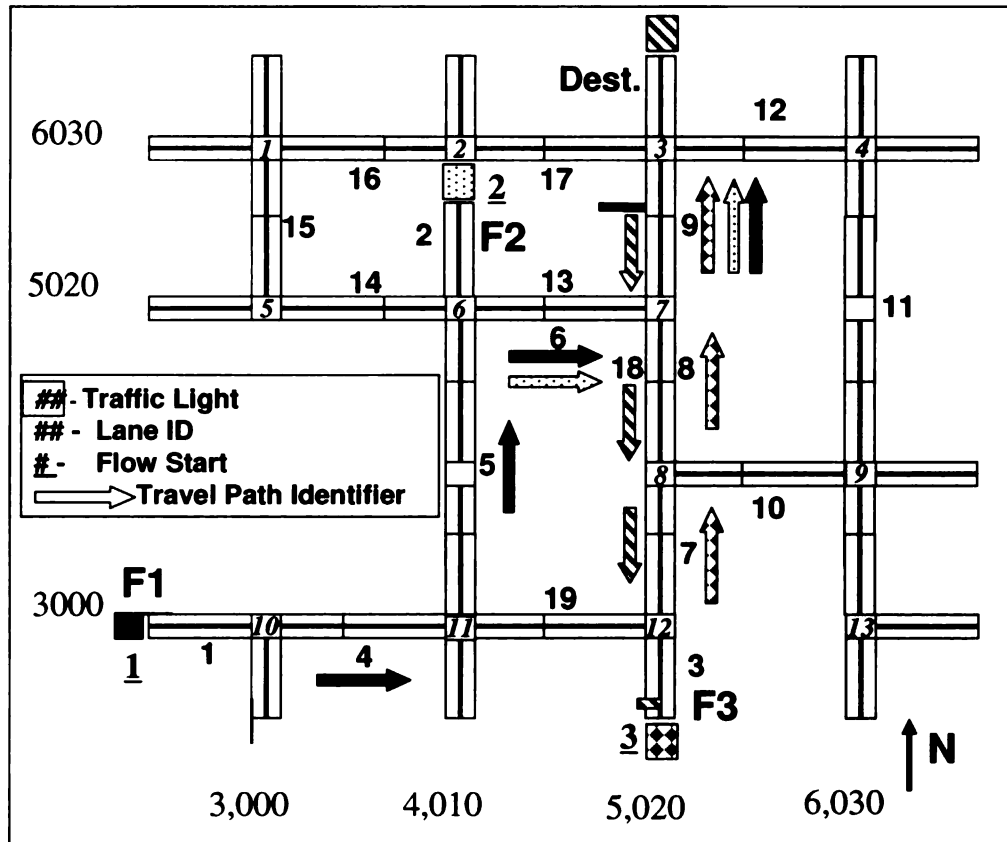


Figure 4-1: Simulated traffic network with relevant markings

In terms of the simulation scenarios used to test the effectiveness of the WiNDCC system, they each use the same traffic network topology and it can be found in Figure 4-1. In this figure, the intersections marked 1 through 13 use the abovementioned traffic light logic. As previously mentioned, the topological, traffic light, and geographical aspects of this topology are enabled with the functions and modules mentioned. A general perspective regarding this topology and the commonalities between the experiments is as follows.

| Traffic Network Characteristic | Setting |
|---------------------------------------|---|
| Per-Link Speed Limit | 20 m/s: Random value selected between 16.75 and 23.25 m/s |
| Traffic Light Timing | Road from 30 to 23: NS Green: 50s EW Green: 100s All others: NS Green: 53s EW Green: 50s All: Yellow: 3s |
| Segment Lengths | Shorter Segments: 1000 m Longer Segment: 2010 m |

Table 4-1: Traffic network parameters

As for the experiments, there are three different classifications designed to test the various aspects of the WiNDCC system. However, the details of each experiment will be left for the individual chapters in which the results are presented. Nevertheless, there are certain traffic network characteristics that will be similar to all experiments. Some are found in Table 4-1; they correspond to the speed limit, traffic light timing, and segment lengths associated with the traffic network. Additionally, there are other markings on this figure that will relate to each of the experimental setups.

To begin with, the shaded squares on the map represent the origination place for the three flows of vehicles that will be used in the experiments and the destination. In the following chapters, the word flow refers to a group of vehicles sharing a common starting and destination point, one of the highlighted origination squares marked 1, 2, or 3 and the highlighted destination. Nevertheless, the box towards the top of the topology denotes the common destination in which vehicles from all flows will look to arrive.

In terms of finding the traffic network wide TDV values needed for route computation, a simulation study was deployed. After running some test scenarios with minimal traffic and the three flows operating individually, it could be seen that the average travel time value for each link was very close to the approximate travel time for a link plus the red time for the traffic light serving the link. Therefore, these quantities are used for the TDV of each roadway. As a consequence the highlighted arrows, which extend beyond each of the flow origination links, represent the theoretical best path that a vehicle will take based on the calculated TDV values and the destination intersection. This determination was made using the path computation procedure, Figure 3-5, with the TDV for each link used as the cost. Consequently, if a vehicle from one of the designated flows travels from source to destination based on the best path logic, it will always take the path indicated by the arrows. Looking ahead to some of the experiments, the input traffic rate for the indicated flows will be varied.

It will also be seen during the presentation of the results, some metrics are presented with respect to the overall performance of the WiNDCC enabled network, and others will be in terms of the individual drivers using WiNDCC. This perspective can be realized by reexamining the architectural walkthrough presented in section 3.2. The service manager is interested in overall mechanism performance, and any vehicle using WiNDCC is concerned with how the system performs subject to its individual travel experience. Nevertheless, to assist with some of the overall system performance metrics, each of the lanes potentially used during the simulation time are labeled with numbers. This will help identify them, as results pertaining to their utilization and individual delay times are examined.

4.4.2 Wireless Networking

In terms of the wireless networking specifications, the IEEE and ASTM-adopted Dedicated Short Range Communication (DSRC) recommended MAC layer protocol is used for each experiment. This protocol is the familiar 802.11 MAC layer specification operating in the distributed, base station-less, mode. In terms of the transmission and interference ranges particular to the ns-2 implementation of 802.11, all nodes use the preset values of 250m and 550m range respectively. Therefore, in terms of the ADI used in WiNDCC operation, a slight change must be considered in regard to the ns-2 implementation of the formula. In specific, the authors of [29] assume that a nodes interference range is equal to two times its transmission range, hence the $2R$ found within the numerator of Figure 2-2. However, in the ns-2 implementation the interference range is slightly more than this value. Therefore when a vehicle is using the ADI within the below mentioned experiments, the $2R$ found within the numerator of the computation is replaced by 550.

Chapter 5: WiNDCC Performance for Handling Traffic

Congestion

In this chapter, the performance of the WiNDCC system will be presented as it relates to congestion within the traffic network. The simulations used in this chapter do not include any traffic events, only the three abovementioned flows with varying traffic input rates. With respect to the algorithms, the link exit logic discussed in section 3.6.1 is responsible for generating the delay messages. The performance due to traffic events or link stoppages is found within the next chapter.

5.1 Simulation Setup

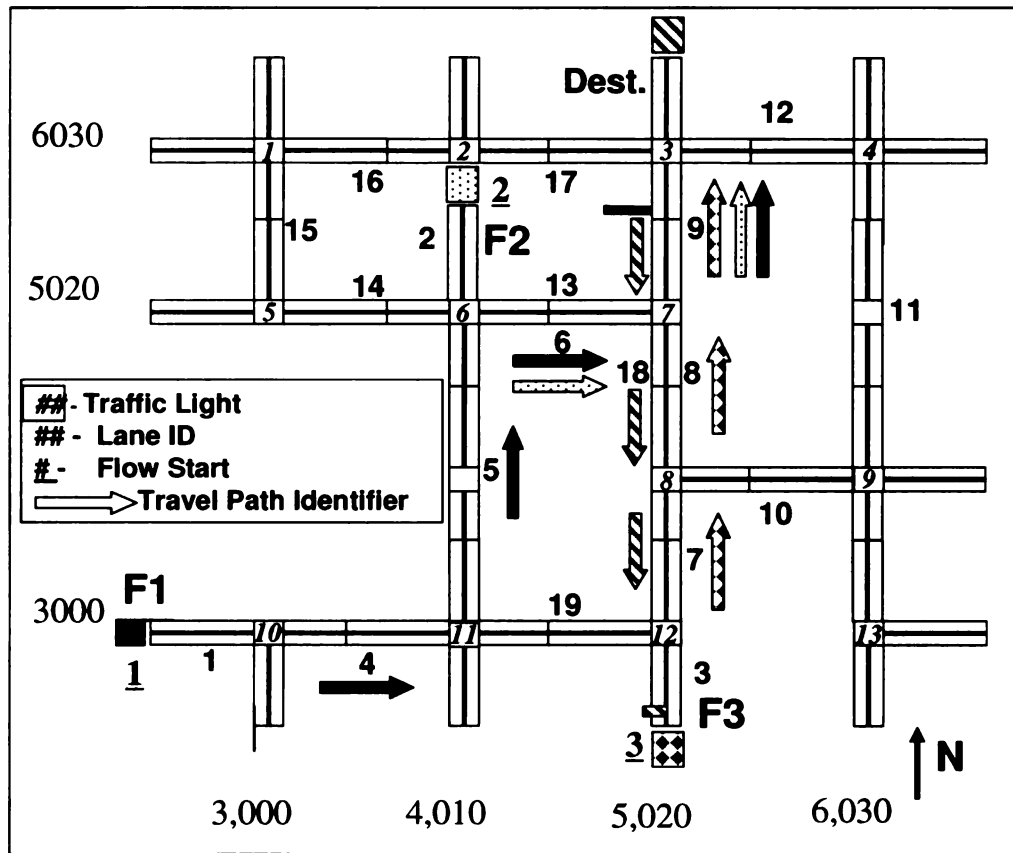


Figure 5-1: Simulated traffic network with relevant markings

As previously seen in section 4.4, the topology used for the traffic congestion oriented simulations is found in Figure 5-1 and operates subject to the specifications given in Table 4-1. Also, the networking settings for the layers operating below the WiNDCC implementation can be found there.

| High | Medium | Low |
|--------------------|----------------------|--------------------|
| .5 Vehicles/Second | .167 Vehicles/Second | .1 Vehicles/Second |

Table 5-1: Vehicular input rates

| Flow ID | Number of Vehicles | Flow Start Time |
|---------|--------------------|-----------------|
| 1 | 200 | 75 s |
| 2 | 180 | 650s |
| 3 | 200 | 450s |

Table 5-2: Vehicular flow specifications

The purpose of the experiments is to determine how well WiNDCC is able to clear up the traffic congestion caused by the three specified input flows, with varying traffic input rates and 100% WiNDCC enablement. Simulations are performed with three traffic input rates, which are denoted by the terms high, medium, and low. To clarify, the traffic input rate for a particular simulation run applies to all flows within the simulated atmosphere and are described in Table 5-1. Also, there is other relevant information relating to the three vehicular flows. This information can be found in Table 5-2 and relates to the amount of simulated vehicles in each flow and the simulation time in which the flow becomes operational. Now, it can be understood the three experimental setups used to gather the results for this chapter.

5.2 User Oriented Performance Metrics

Although the per vehicle end to end travel time and distance are certainly important quantities to the system operator, the results are more user driven and are presented within this section. The results include the average distance and delay, along with distributions for both quantities. Also, another result is plotted that highlights the delay

vs. distance tradeoff associated with traffic congestion mitigation, subject to the arguments presented in section 1.1.1.

In addition, to avoid redundancy while presenting the results, the majority of the findings will be in terms of the high traffic input rate, while considering WiNDCC without partition bridging. Additionally, with regard to the WiNDCC system quantity of ICI, a value of .25 is used for the initial results. Then, results will be shown that depict the effects of partition bridging, varying traffic input rates, and various ICI values.

5.2.1 Travel Delay Improvement

The WiNDCC overall system goals, as described in Chapter 1, relate to travel delay mitigation. Therefore, the first result will deal with the average end to end travel delay mitigation. As previously mentioned, these experiments use the high traffic input value and an ICI value of .25. The primary comparisons are made between No Traffic Congestion Control (NTCC) and WiNDCC.

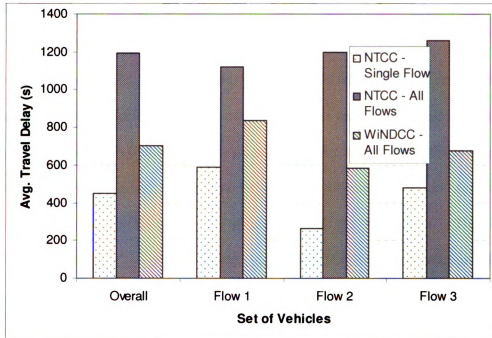


Figure 5-2: Travel delay benefits, highly congested traffic network

The average end to end travel delay can be found in Figure 5-2; in terms of the plot axes, the x axis represents the set of vehicles being described and the y axis denotes the average travel delay. A vehicles delay value corresponds to the time when it leaves the first intersection it encounters minus the time when it enters intersection 3. To clarify, the data series and results description is as follows.

The first series (NTCC – Single Flow) represents the single flow experiments, when only the indicated flow is residing in the traffic network and the travel is dictated by the best case delay numbers. These data points represent the best case travel operation for that flow, since it is the only one using the network. In addition, when considering the single flow data point within the overall vehicle breakdown, this corresponds to all simulated vehicles when their respective flow inhabits the traffic network alone. It can

be clearly seen that the average delay for this data series is much lower than the others, on an overall and per flow basis, which is to be expected.

The second series (NTCC – All Flows) corresponds to when all flows are operating in the network at the same time and the travel is dictated only by the best case delay numbers. That is, the series considers all flows using the theoretical best paths as marked in Figure 4-1. As one can see, the average delay values associated with this series are much higher than the NTCC alone, on an overall and per flow basis. This is a straightforward result of the increased traffic along the links in which multiple flows share.

Finally, the last series indicates the WiNDCC enabled traffic congestion mitigation that is applied to the scenario. It can be clearly seen that by using WiNDCC, the accumulated traffic delay due to all flows being present in the traffic environment is reduced. In other words, after congestion is detected in the traffic network and vehicles begin to use the other travel paths to reach the destination. That is the goal of the WiNDCC system and it is being achieved by way of the designed application and network layer protocols, combined with the route computation process.

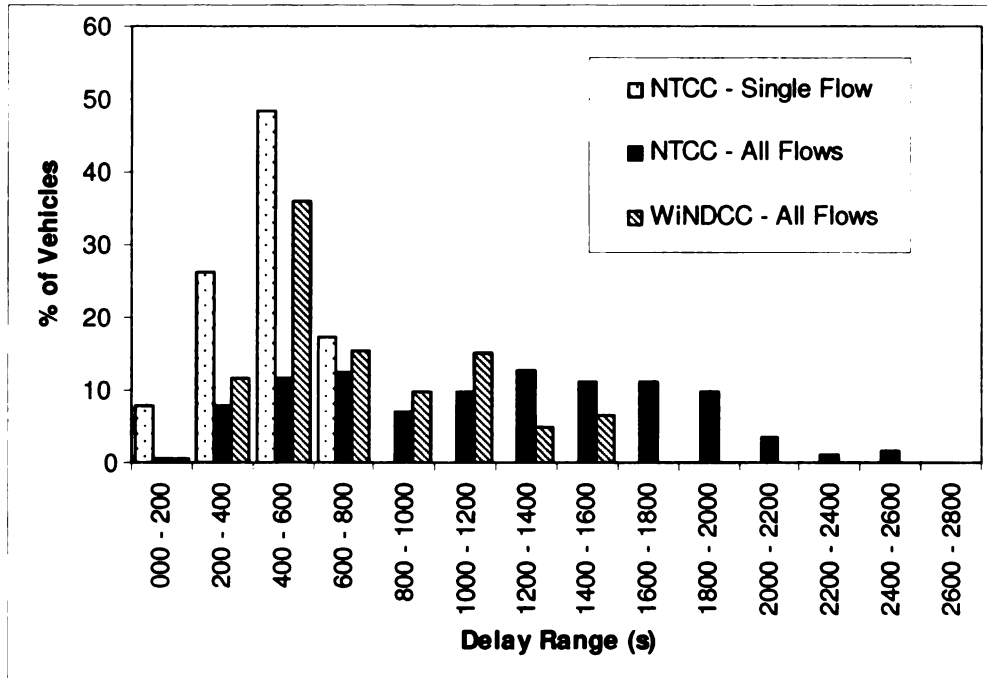


Figure 5-3: Overall travel delay distribution, highly congested traffic network

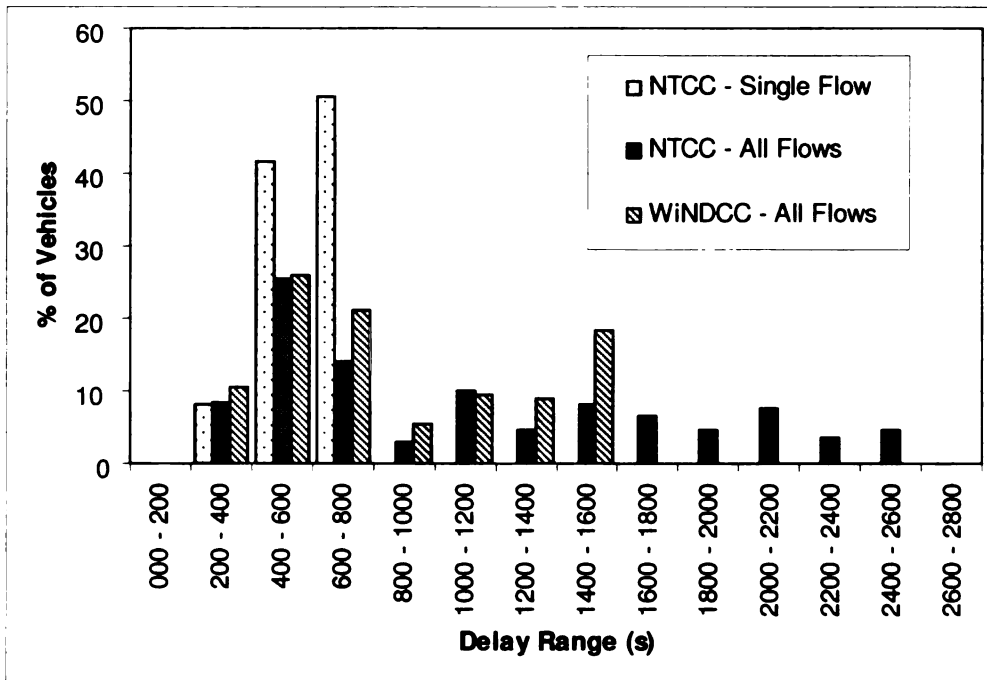


Figure 5-4: Flow 1 travel delay distribution, highly congested traffic network

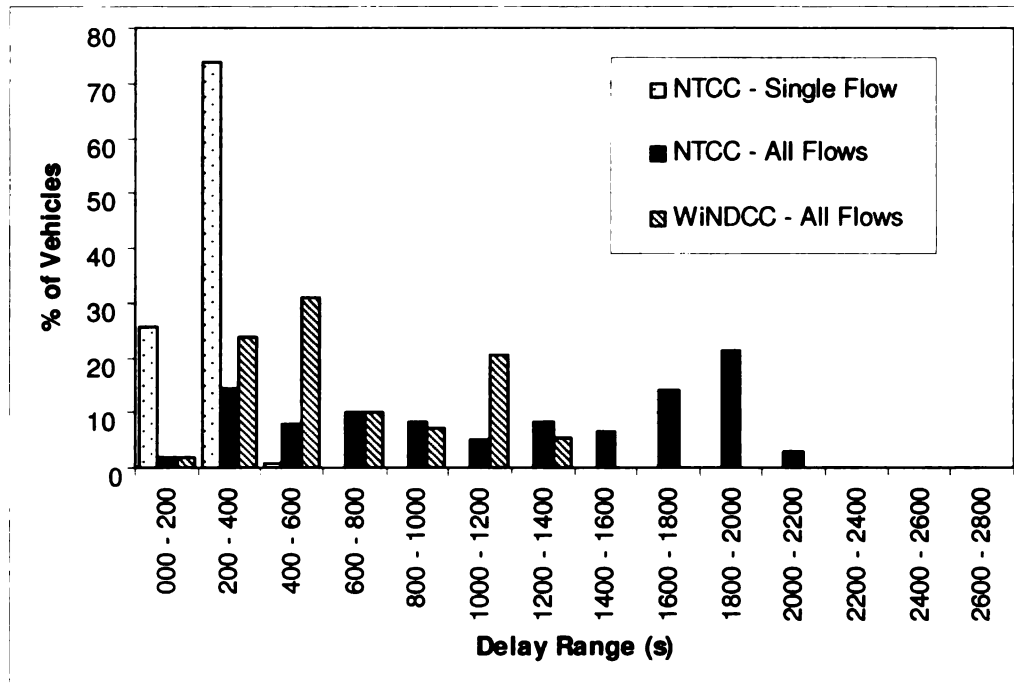


Figure 5-5: Flow 2 travel delay distribution, highly congested traffic network

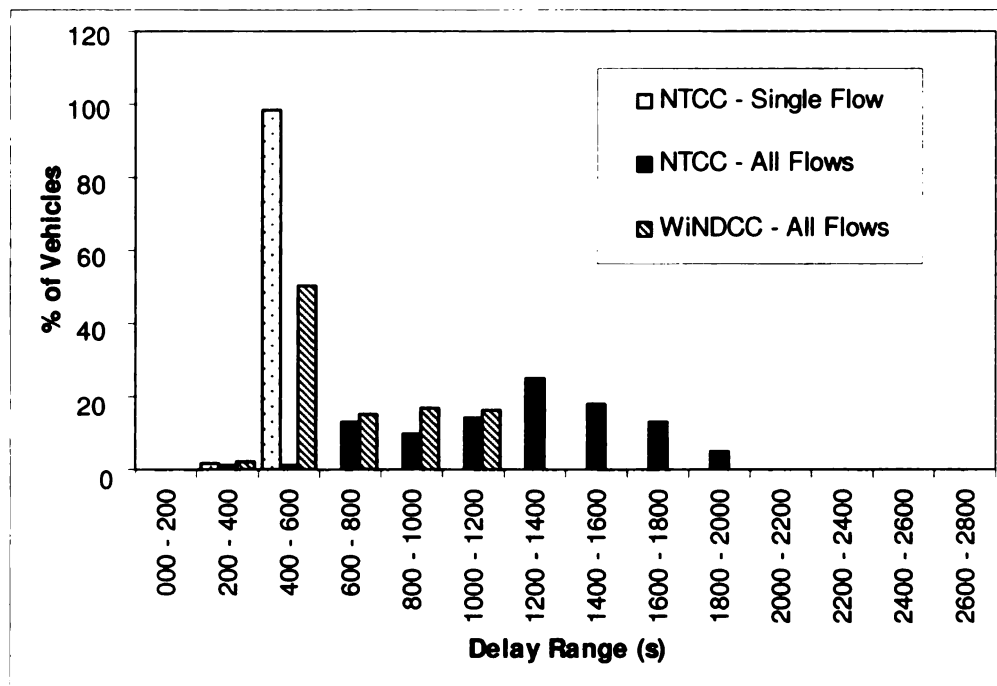


Figure 5-6: Flow 3 travel delay distribution, highly congested traffic network

Another result that highlights the user oriented delay mitigation capabilities of WiNDCC is the end to end delay distribution. From this perspective, the recorded delay values used to compute the abovementioned averages can be better visualized. The overall and per flow delay distributions can be found in Figure 5-3 through Figure 5-6. On the x axis is the delay categories and the y contains the percentage of vehicles arriving during that breakdown. Also, the data series relate to the same quantities as previously mentioned.

By viewing the results, it can be seen that the WiNDCC system improves the delay distribution on an overall and per flow basis, with respect to the NTCC all flows case. In specific, WiNDCC moves the delay distribution closer to the left in comparison to the congested case, indicating that vehicles are able to avoid the longer delay times associated with using the traffic network without the mechanisms in place. Additionally, the NTCC for the single flow cases is shown to give the reader an understanding of the distribution under the best case operation.

5.2.2 Travel Distance Degradation

As mentioned within section 1.1.1, in most cases delay mitigation results in the assisted vehicles traveling a longer distance to arrive at the destination, compared to those who remain on the more congested theoretical best paths. It is an unavoidable aspect of delay mitigation within traffic networks. In this section, results are shown that highlight this activity within the given experimental setup.

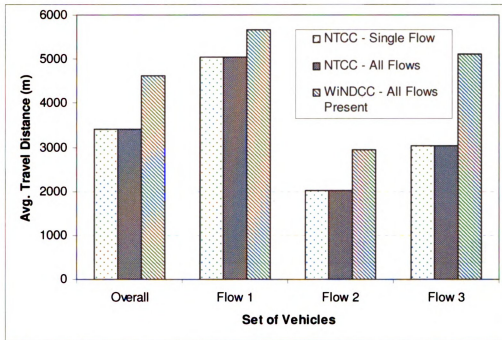


Figure 5-7: Travel distance degradation, highly congested traffic network

The average travel distance, under the identical simulation parameters for the previous results, is shown in Figure 5-7. As for calculating the travel distance, a vehicles traveled distance corresponds to the distance it has traveled from when it leaves the first intersection to intersection 3. Unlike the average travel delay, both the NTCC with each flow acting individually and NTCC with all flows display equal average travel distance. By considering the principles of the two scenarios, the reason behind this is very basic. That is, both definitions require vehicles to travel via the theoretical best paths the traffic network allows, and these paths are the same regardless of the traffic conditions found within the network. Therefore, the average travel distance for the NTCC cases are exactly the same. As for the travel average distance when WiNDCC is applied, it increases in comparison to the other cases. That is because longer alternate paths are being used by vehicles to avoid the induced traffic congestion.

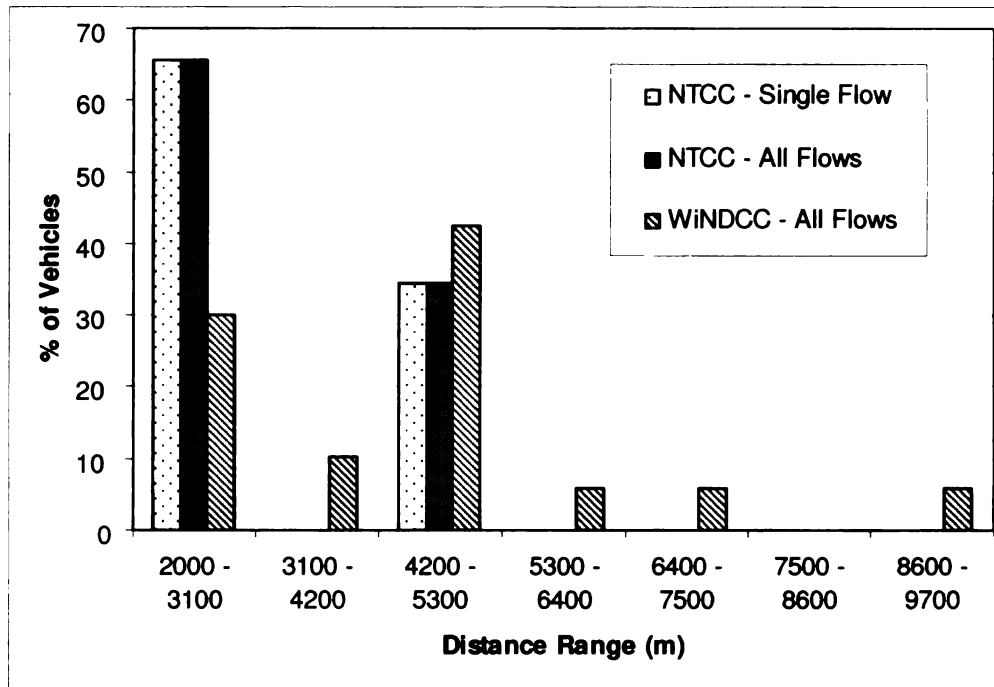


Figure 5-8: Overall distance distribution, highly congested traffic network

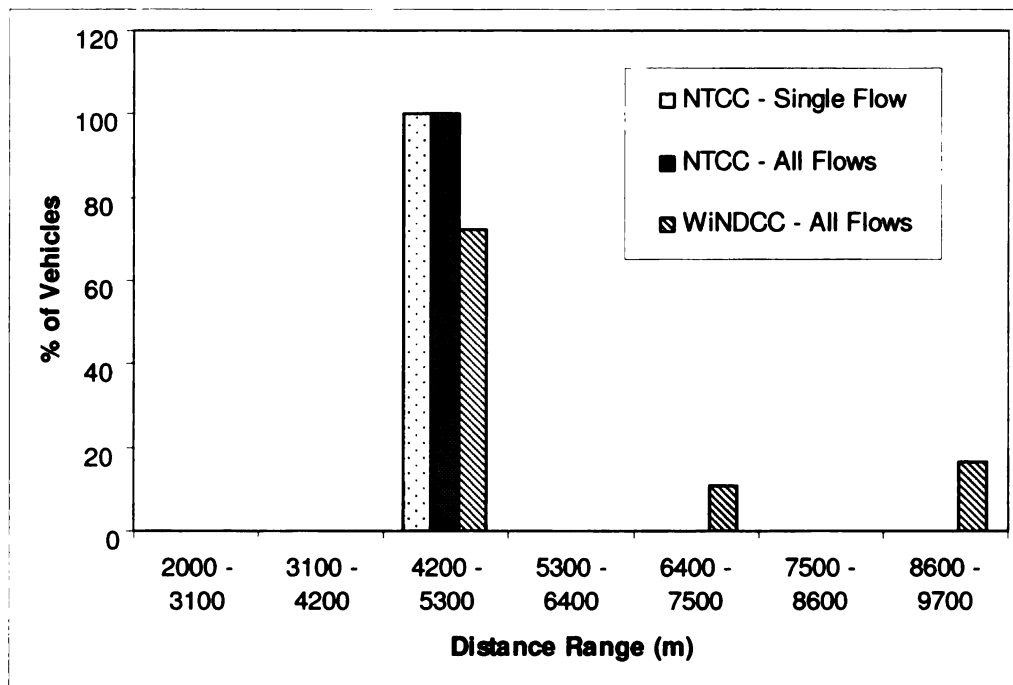


Figure 5-9: Flow 1 distance distribution, highly congested traffic network

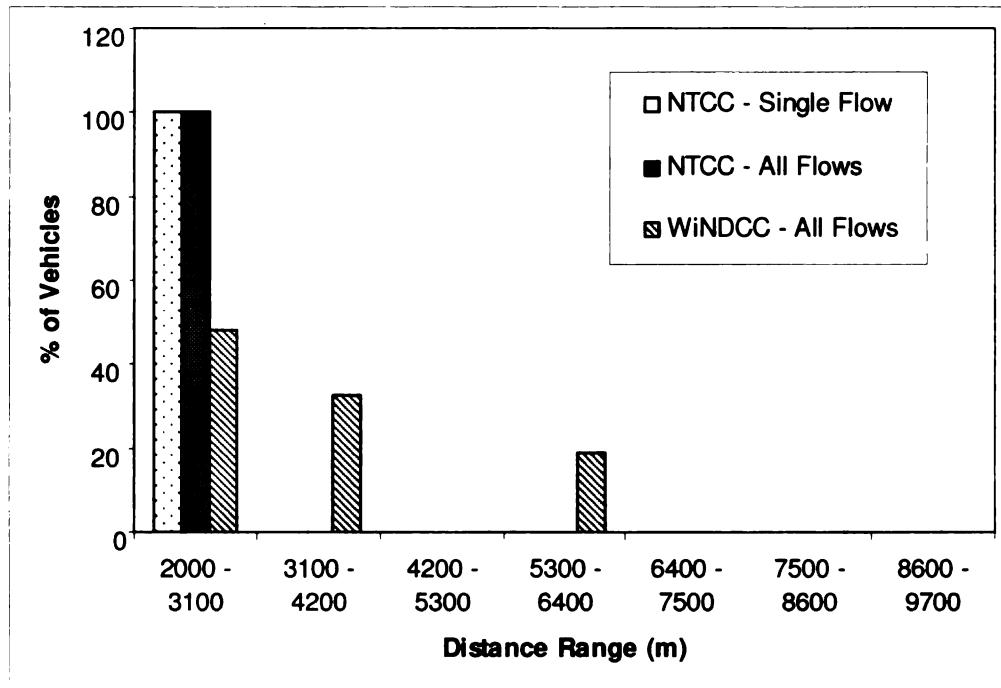


Figure 5-10: Flow 2 distance distribution, highly congested traffic network

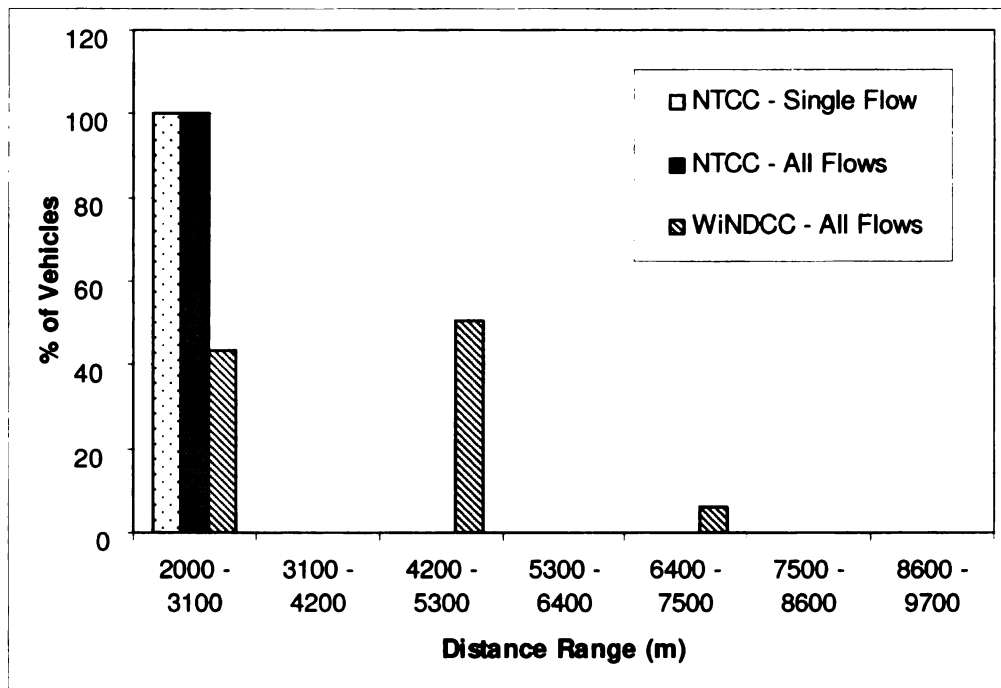


Figure 5-11: Flow 3 distance distribution, highly congested traffic network

To add more understanding to the average distance numbers, the overall and per flow distance distribution has also been plotted and can be found in Figure 5-8 through Figure 5-11. On the plotting axes, the x axis represents the distance breakdown and y denotes the percentage of vehicles arriving within this distance range. As expected, the WiNDCC enabled experiments move each distance distribution to the right, indicating that vehicles are deviating away from the pre computed best path and are traveling longer distances to alleviate their end to end travel delay. Also by viewing the per flow distance distributions, it can be seen how many vehicles from a particular flow switch to another path or remain on the primary path. Additionally it can be understood which path the vehicles have taken, when the topology and potential alternate paths are considered for each flow. For example, for flow 1 the vehicles within the 6400 to 6500 breakdown traverse intersections 10, 11, 6, 5, 1, 2, and then 3. While the remaining vehicles within the 8600 to 9700 breakdown traverse intersections 10, 11, 6, 7, 8, 9, 4 and then 3. The same can be deduced from the distance distribution for the other two flows.

5.2.3 Delay vs. Distance Representation

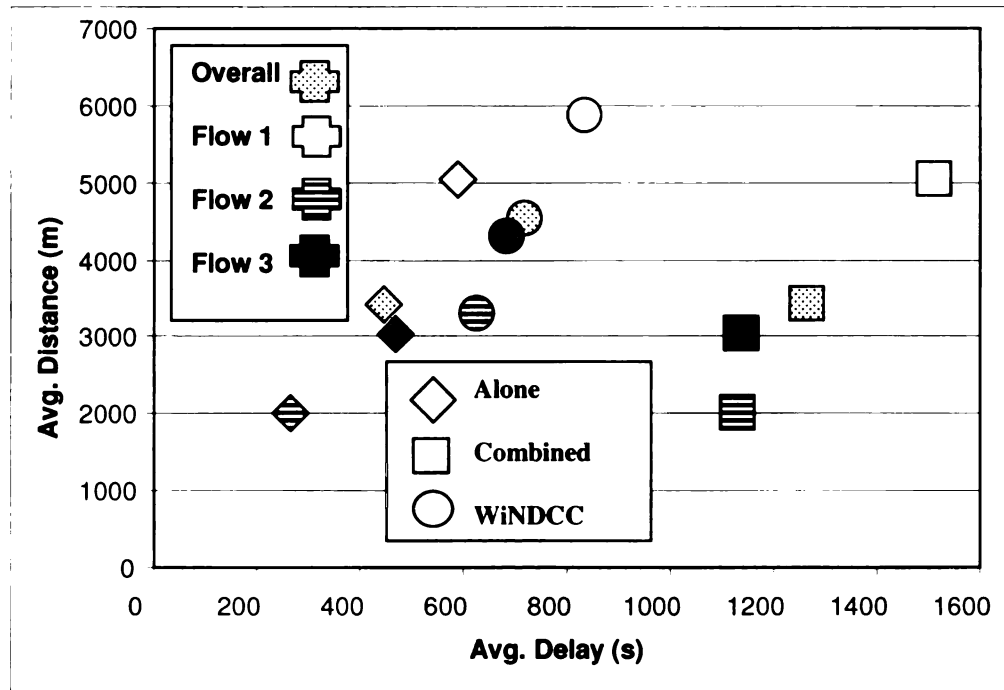


Figure 5-12: Delay vs. distance plot, highly congested traffic network

To summarize the abovementioned, the average delay vs. average distance for relevant simulation setups is shown in Figure 5-12. In this figure the diamonds represent the case when the indicated flows use the traffic network alone. The squares represent the congested case where all flows use the traffic network at the same time, and the circles indicate WiNDCC influenced traffic behavior. Also, each highlighting pattern indicates a vehicular breakdown. As it can be seen for both the overall and per flow categories, the average travel distance is larger. Nevertheless, the average delay is also decreased. Therefore, it can be seen from another vantage point the effectiveness of the WiNDCC system at mitigating the traffic congestion within the highly congested traffic scenarios, subject to the arguments presented in section 1.1.1.

5.3 Operator Oriented Performance Metrics

In this section, system operator or management oriented results will be shown for the highly congested traffic network. These results differ from the aforementioned ones, because they consider operational aspects of the entire traffic network and the overall performance of the WiNDCC enabled vehicles. Also, the data series are NTCC and WiNDCC, both with all flows residing in the traffic network.

5.3.1 Lane Utilization and Delay

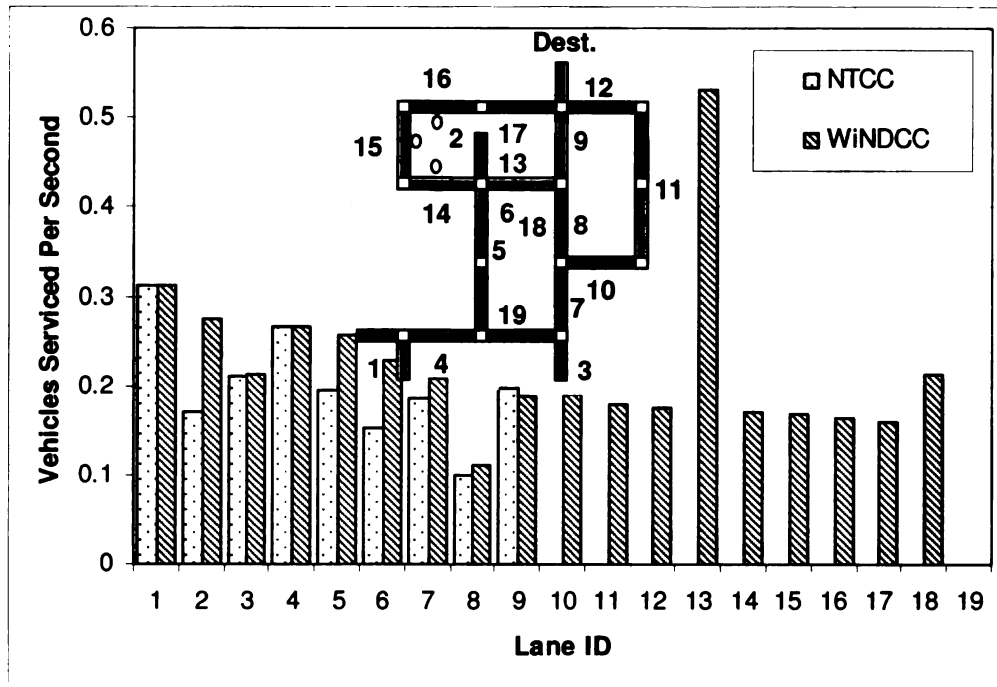


Figure 5-13: Per lane utilization for highly congested network

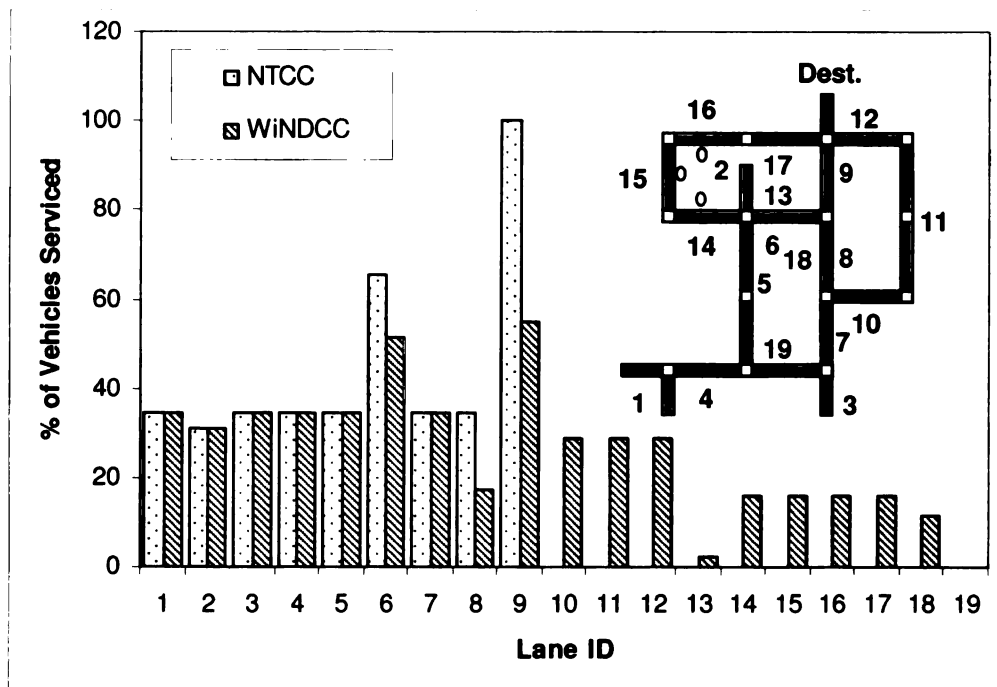


Figure 5-14: Per lane service percentage for highly congested traffic network

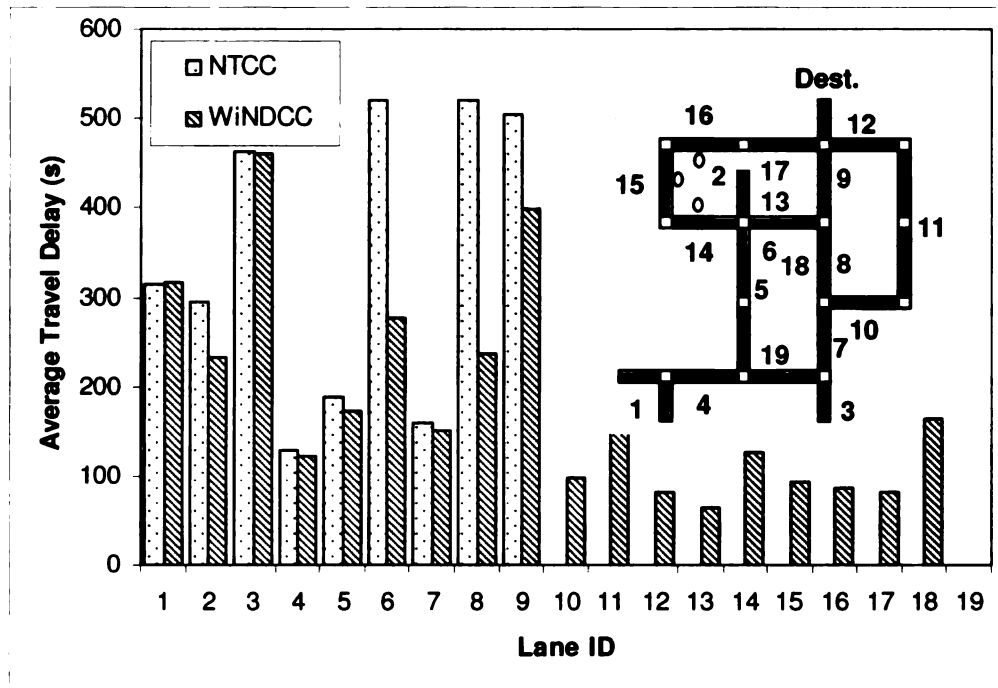


Figure 5-15: Per lane delay for highly congested network

By considering the way WiNDCC and other traffic delay mitigation schemes actually alleviate the travel delay, it is evident that traffic originally intended for a particular path is distributed along other links in the traffic network. From an operator perspective, this is desired since more of the tax payer supported roadways will be used to deliver vehicles to destinations, while the overall traffic delay experienced by drivers is decreased. For the scenario in which the previous results were found, a per lane utilization plot can be found in Figure 5-13. To clarify, the utilization for a lane is the amount of vehicles serviced by a lane divided by the amount of time that it serves vehicles. In Figure 5-14, a plot is given that represents the percentage of total vehicles that are serviced by a particular lane. And, a per lane average delay plot is found in

Figure 5-15. In the plots, the lane numberings and topology are relisted to assist the reader with understanding the results.

The first 9 lanes are the ones found by best path computation and that are used in the NTCC case. It can be seen that the utilization for the shared and more congested of these links is improved when WiNDCC is equipped. It can also be seen by the percentage of vehicles serviced, that with WiNDCC equipped congested roadways experience a decrease in the amount of vehicles they service. As a result, the delay is also dramatically improved, since vehicles are using other links instead of those for travel. Also subject to the simulation setup and operational aspects of a route guidance system, WiNDCC forces other lanes to be utilized within the simulation area, hence the data values for lanes 10 through 18 that are not seen without traffic congestion control. Therefore, one can see that WiNDCC effectively transfers the utilization and delay of the links in the pre computed best path links to other roadways within the topology.

5.3.2 Vehicular Throughput

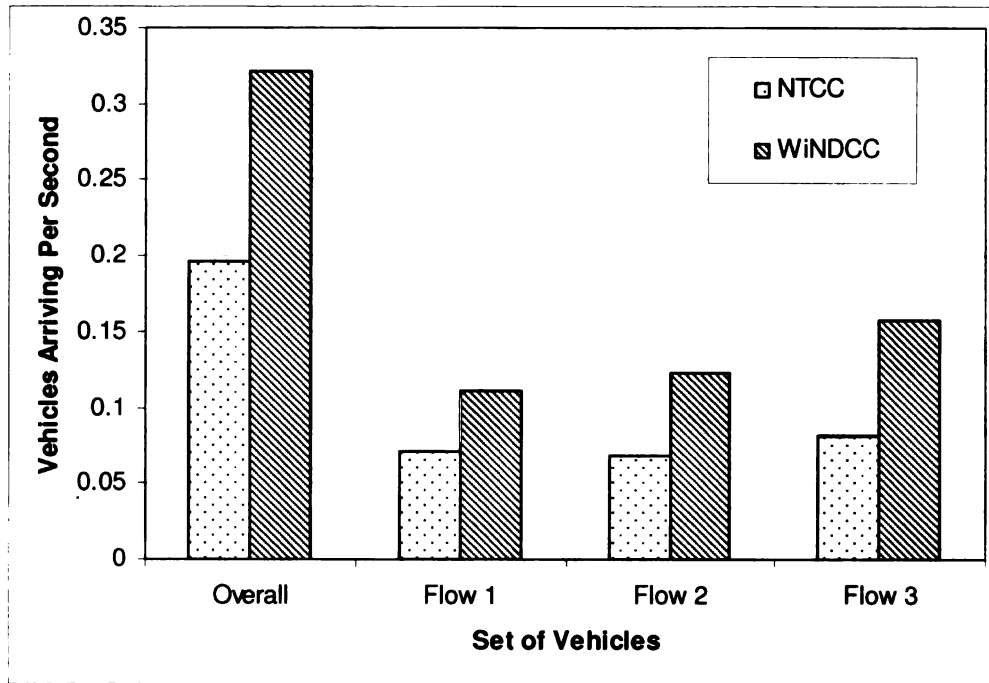


Figure 5-16: Vehicular throughput for highly congested traffic network

Another operator quantity that is examined corresponds to the vehicular throughput or destination arrival rate and is found in Figure 5-16. This quantity is simply the amount of vehicles successfully delivered to the destination divided by the amount of time it takes for them to be delivered, in seconds. Within the plot area, the x axis corresponds to the set of vehicles and y denotes the amount of vehicles arriving per second. Although the numerator of the computation remains the same for each experiment, the denominator changes, since when mitigation is applied the vehicles arrive in a shorter amount of total time. It can be seen that on an overall and per flow basis the destination arrival is improved with WiNDCC enabled.

5.4 Effects of Initial Congestion Indicator on End to End Delay

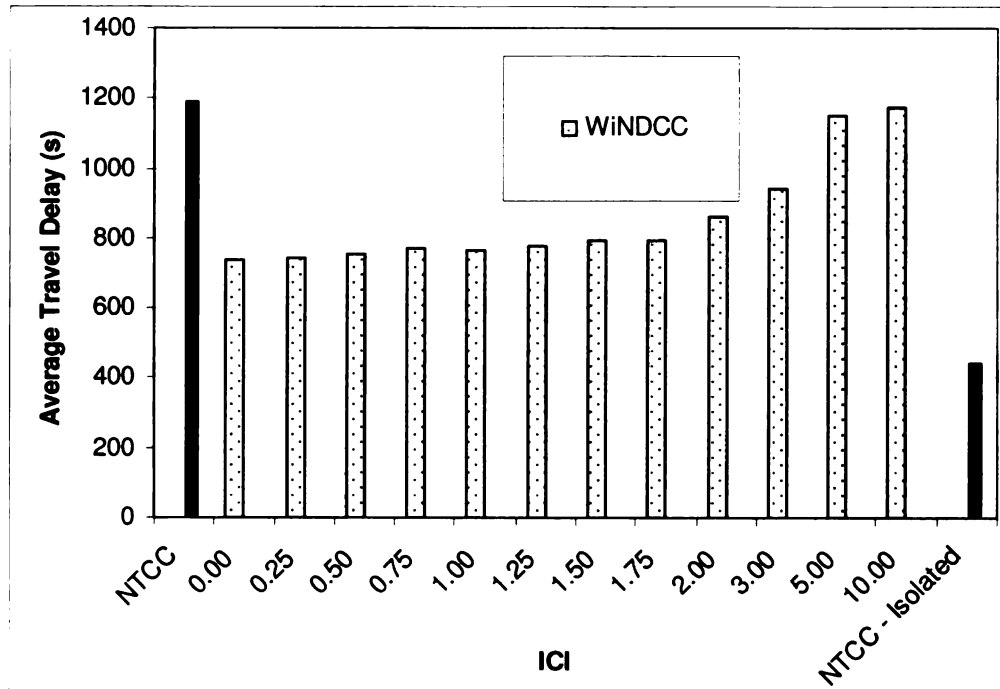


Figure 5-17: Effects of ICI on overall travel delay

The next result demonstrates the effects of the ICI described in section 3.6.1, the WiNDCC system quantity that describes when vehicles will begin broadcasting traffic delay information about a particular link. In short, a large ICI value allows more congestion to develop in a link before broadcasting any information. The results thus far have used an ICI value of .25. Nevertheless, Figure 5-17 is included and shows the overall end to end travel delay for various ICI values in the highly congested traffic network. The main data series is WiNDCC, and it is evident that as ICI increases so does the overall travel delays. However, three other data points are included that help put in perspective WiNDCC performance. The first, listed on the far left is NTCC with all flows present, and on the far right is the overall delay with each flow occupying the network alone. It can be seen that as the ICI increases, the delay begins to look like that

for NTCC combined, as one would suspect due to the lack of information being broadcast about the traffic network. The ICI equal to 0.00 data point represents an experimental scenario where each vehicle broadcasts its delay information after exiting every link. As one can see, the delay is not mitigated any better than WiNDCC with an ICI value of .25. This finding validates the logic used in the link exit strategy, along with the ICI utilization, since the congestion is being adequately mitigated with much less information being broadcast into the network. This finding will be covered in more detail in Chapter 8.

5.5 Results with Partition Bridging and Varying Traffic Input Rates

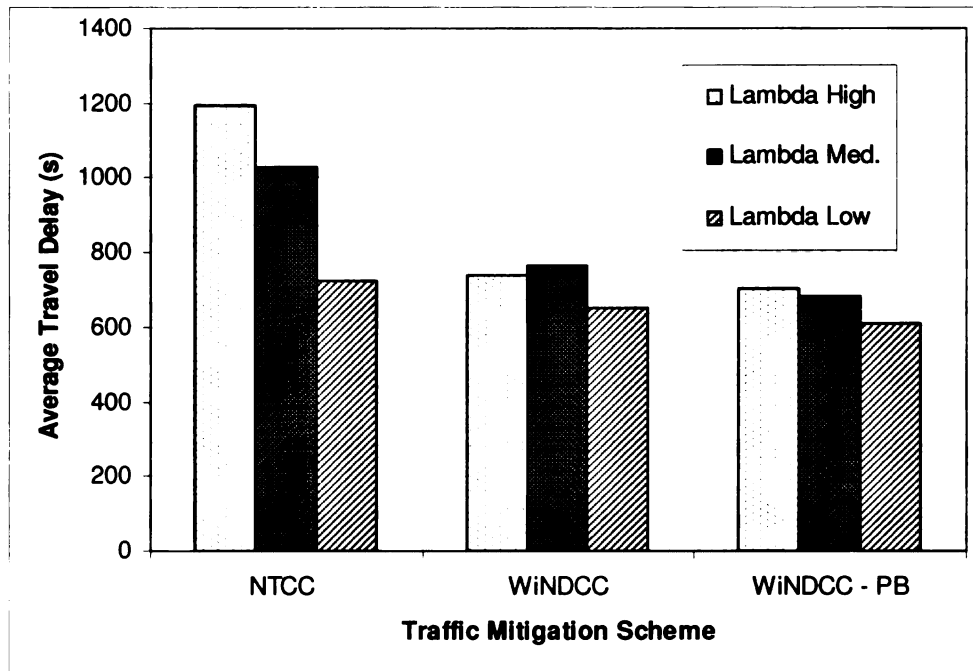


Figure 5-18: Delay with varying vehicular input rates and mitigation schemes

In terms of the vehicular input rates seen in Table 5-1, results concerning them and the partition bridging extension, described in section 3.7.4, of the forwarding algorithm are plotted in Figure 5-18. In the figure, the x axis represents the various mitigation schemes and the y axis is the average overall travel delay. By closely viewing the results, it can be seen that partition bridging assists normal WiNDCC with medium and low traffic input rates; although, the network is less congested as seen by the NTCC category. This follows in line with the purpose of the partition bridging algorithm. That is, the effect of the partition bridging is most evident when the network is more partitioned in the traveling direction, such as the medium and low input rates. For the high input rate the effect would be minimized because the network is much less partitioned than in the other cases.

Chapter 6: WiNDCC Performance for Handling Traffic

Events

In this chapter, WiNDCC effectiveness will be evaluated with a traffic event in the network. In terms of the WiNDCC application layer algorithms, this experiment will test the event generation scheme of section 3.6.2. Results similar to those for the congested case will be presented and discussed, along with an initial description of the revised simulation setup. As was done earlier, most results will be in terms of the high traffic input rate case. Then, perspective will be given in terms of each traffic input rate used in this scenario.

6.1 Simulation Setup

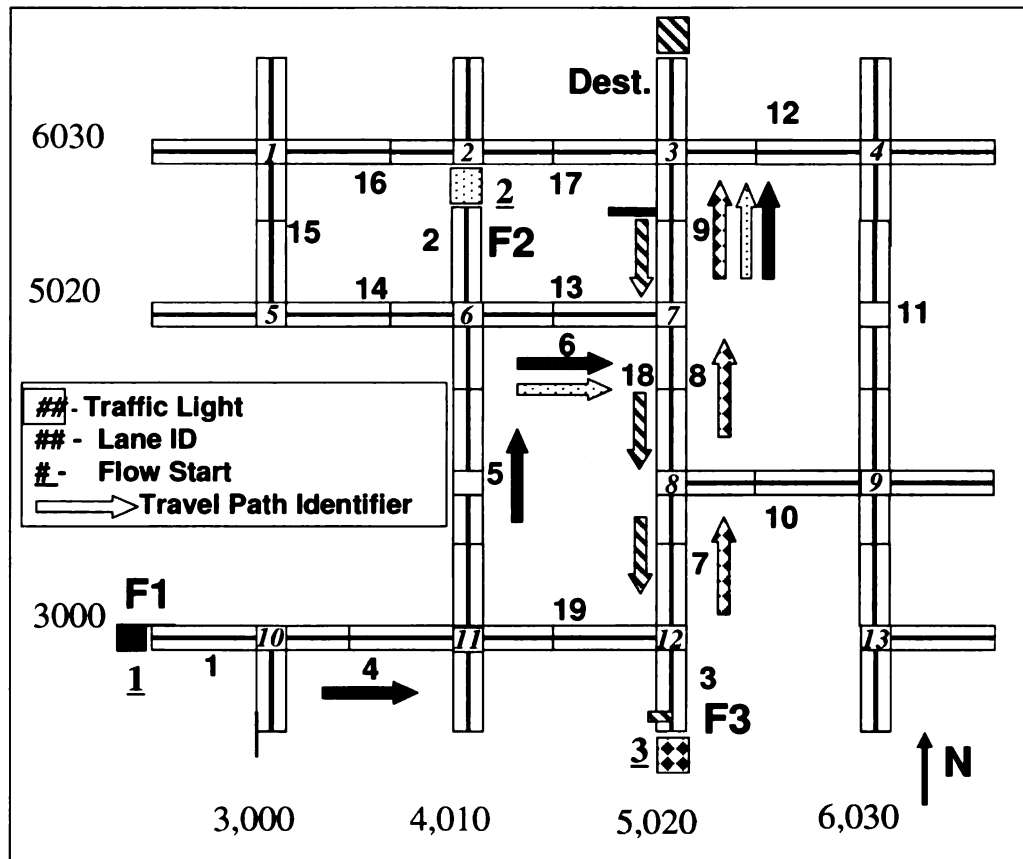


Figure 6-1: Simulated traffic network with relevant markings

For the event based experiment used to gather the results for this chapter, the same topology and underlying characteristics are used from Figure 4-1, Table 4-1, Table 5-1, and Table 5-2. In addition, the event scenario is as follows and the topology is relisted in Figure 6-1. In terms of the geographic location of the event, it will happen 850 meters into the link between intersection 7 and 3. As a visual aid, this area is marked by the line near the indicated link in Figure 6-1. The event will affect the first vehicle to reach this point and will last for about 690 seconds, equal to around 11.5 minutes. After the event is concluded, the front vehicle will proceed as planned to the destination area. Also, in terms of the traffic input rates, high and low were considered for the event case.

6.2 User Oriented Performance Measures

As previously discussed, the user oriented results highlight the ability of WiNDCC to affect the travel quality of individual drivers. For the event case, with high traffic input rate, the user results are as follows. However since the result is not as relevant for the event case, the NTCC with flows acting individually will not be included in them. Therefore, NTCC all flows will be compared to the data with all flows using the WiNDCC system.

6.2.1 Travel Delay Improvements

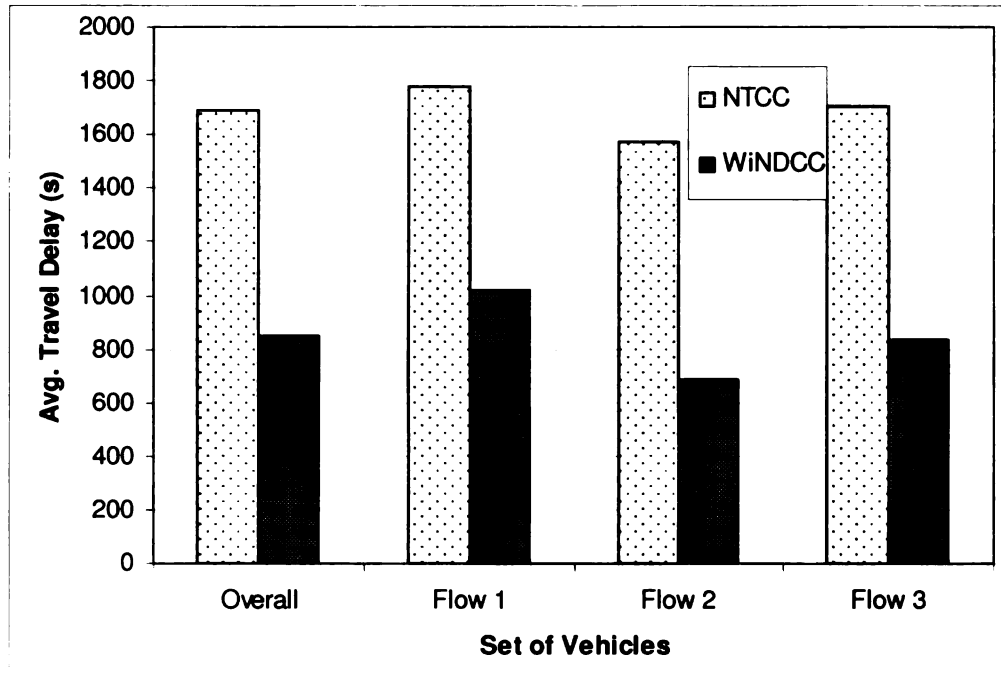


Figure 6-2: Average travel delay with event present

The average travel delay plot can be viewed in Figure 6-2 and has the same axes as seen in the average delay for the congested case. By inspecting the delay values associated with the NTCC case, the very high delay values are a result of the event introduced into the traffic network. As one can see, the WiNDCC system is successfully able to mitigate this delay on an overall and per flow basis. This is a testament to the combined event generation algorithm and underlying network layer operations that guide vehicles away from the congested area to ones that are moving within the traffic topology.

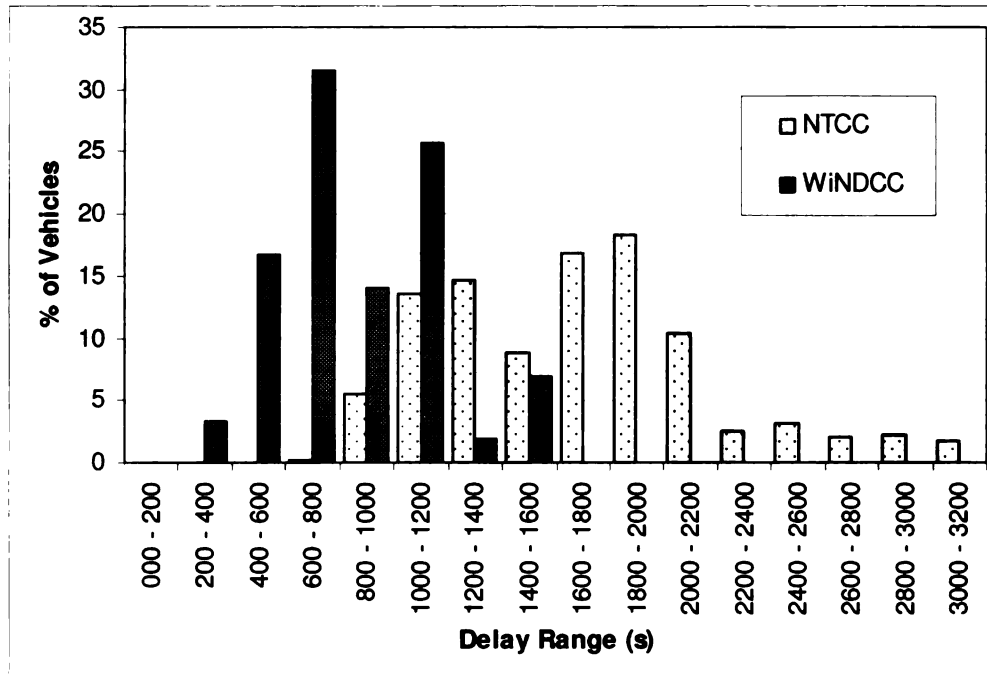


Figure 6-3: Travel delay distribution with event present

The overall delay distribution further supports the numbers seen in the average delay results and can be found in Figure 6-3. That is, based on the reported delay values, much less vehicles experience the extreme delay values caused by the event within the travel network when WiNDCC is equipped.

6.2.2 Travel Distance Degradation

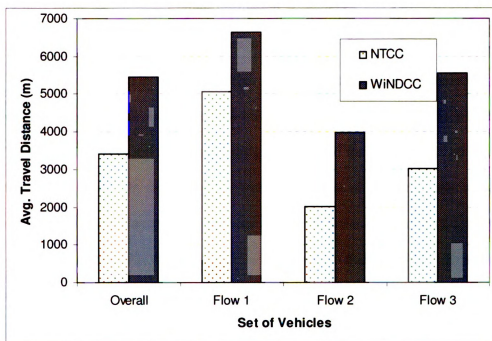


Figure 6-4: Average travel distance with event present

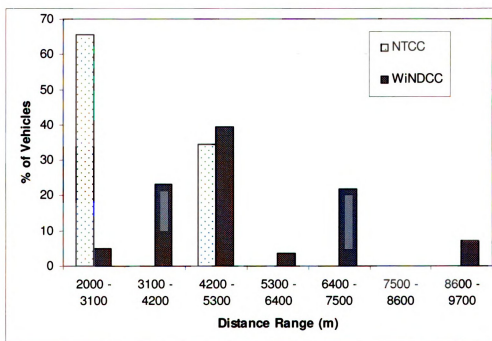


Figure 6-5: Travel distance distribution with event present

The travel distance is also degraded, when compared to those corresponding to the theoretical best paths, when travel delay mitigation is achieved due to the event within the traffic network. The average travel distance and overall distance distribution can be found in Figure 6-4 and Figure 6-5. They both support the arguments presented in this thesis about the effects of alleviating the individual travel delay experienced by travelers. That is, WiNDCC travelers travel a longer distance to avoid the event, from an overall and per flow perspective. In fact, very few vehicles remain on the originally selected travel paths, which can be understood by viewing the distribution and visualizing the extreme shift to the right in the WiNDCC data, with respect to that of NTCC. This also is in response to the event within the network.

6.3 Operator Oriented Performance Measures

Here, the results that would most interest the system enabler will be presented. They are similar to those found within the same category of the congestion case.

6.3.1 Lane Utilization and Delay

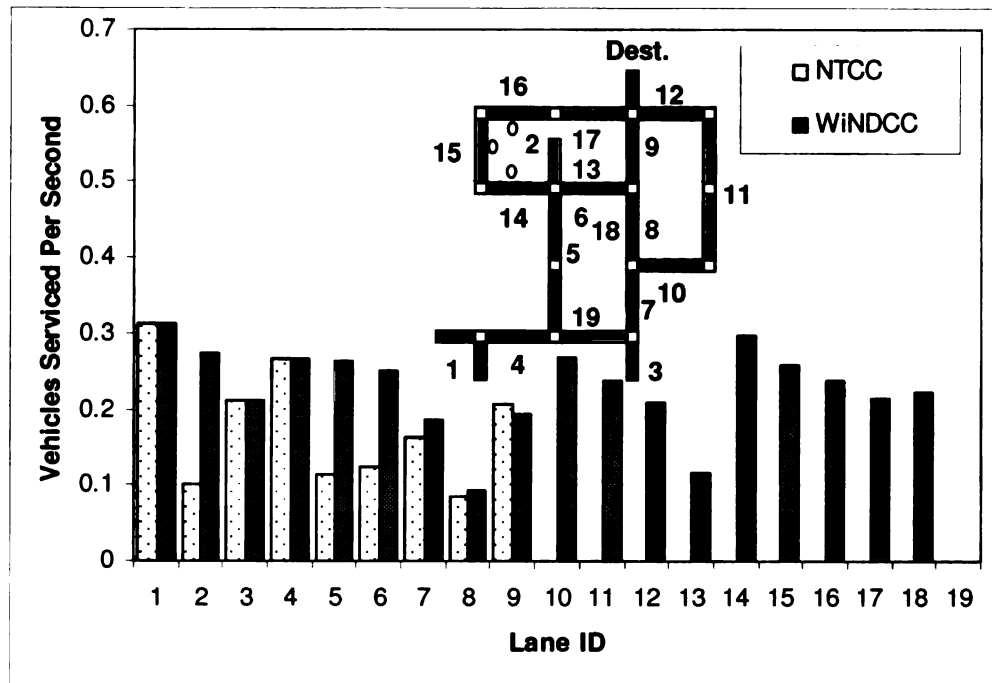


Figure 6-6: Per lane utilization with event present

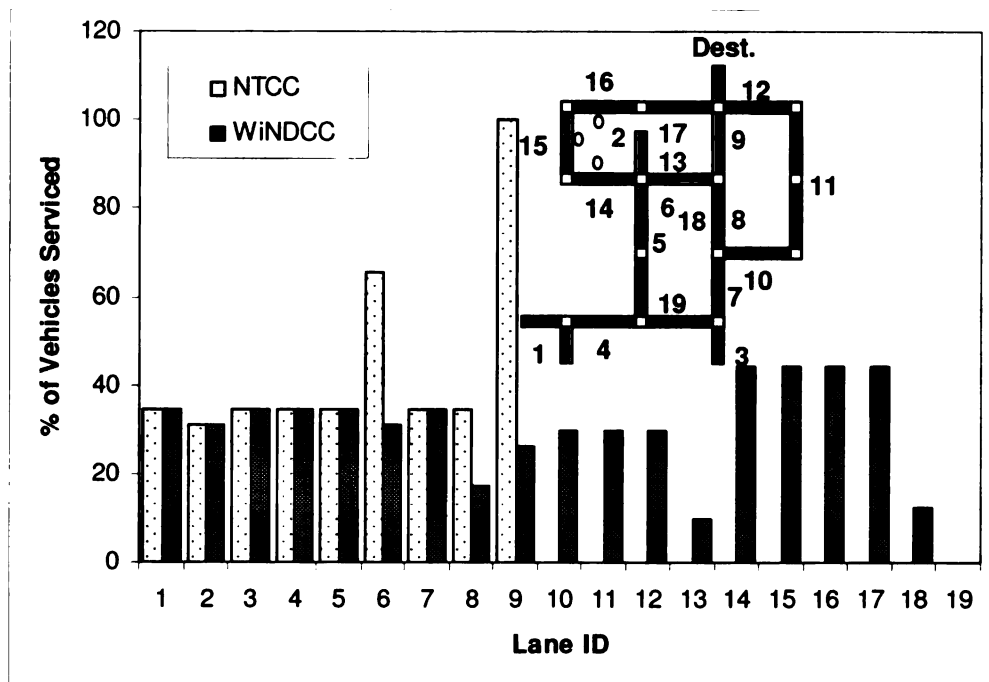


Figure 6-7: Per lane service percentage

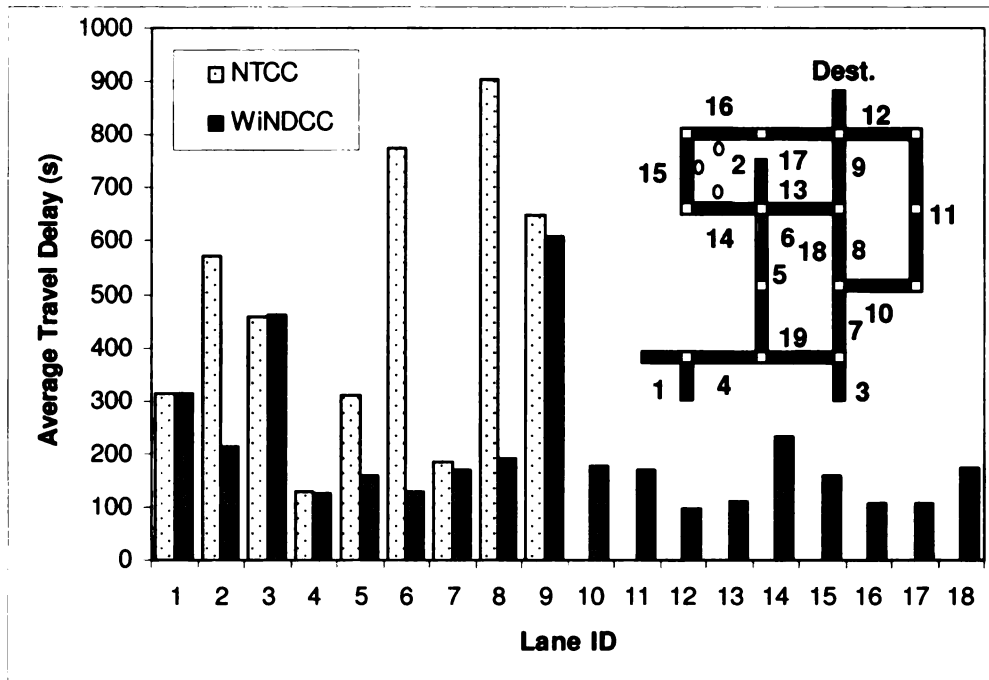


Figure 6-8: Per lane delay with event present

The lane utilization and delay comparing the NTCC congested and WiNDCC enabled cases can be found in Figure 6-6, Figure 6-7, and Figure 6-8. By viewing these results, it can also be understood the per lane traffic network operation due to the event. WiNDCC betters the utilization while also decreasing the delay. The system also, as a result of rerouting vehicles around the event site, utilizes other lanes to help decrease the end to end and per lane travel delay, which can be seen by examining the utilization and percentage serviced results. These results are vital to a network operator, since the effects of the delay are mitigated and the traffic network is more usable as a result of the WiNDCC enablement.

6.4 Vehicular Throughput

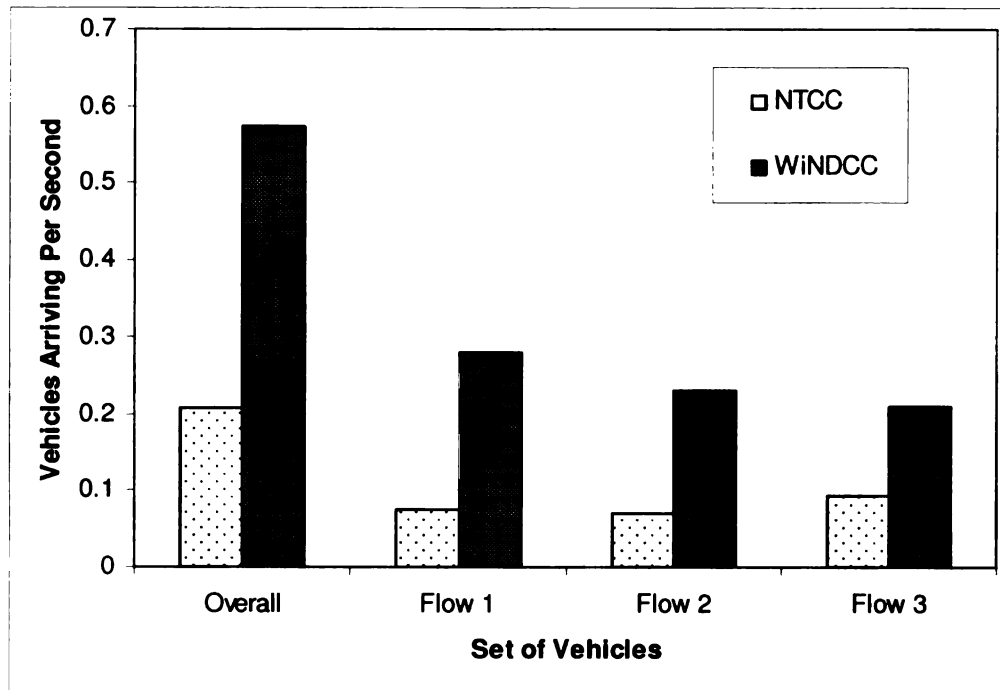


Figure 6-9: Vehicular throughput with event present

The vehicular throughput is greatly improved when applying WiNDCC logic to the event induced simulation scenario. The result can be found in Figure 6-9 and shows that the WiNDCC enabled vehicles arrive at the destination at a much faster rate than with the event present in the network. This result holds true on an overall and per flow basis. This improvement, from the network operator perspective, reemphasizes the effectiveness of WiNDCC when events are present in the network that slow or stop traffic flow. The throughput improvement happens due to the redirection of traffic within the roadway system, which decreases the amount of time required to deliver vehicles to the destination.

6.5 Results with Partition Bridging and Varying Traffic Input Rate

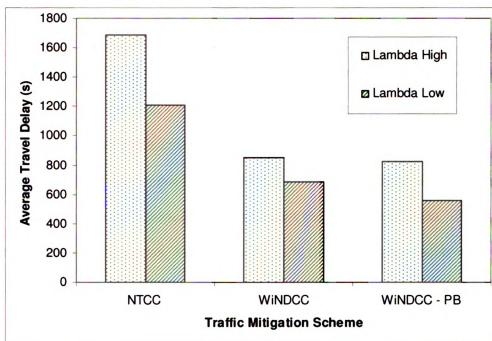


Figure 6-10: Delay with varying vehicular input rates and event present

The results including high and low input traffic rates with partition bridging, described in section 3.7.4, can be found in Figure 6-10. Just as was seen in the congestion only case, the partition bridging assists more when the vehicular input rate is lower. This is a result of increased partitioning within the traffic network. Therefore, the effects of partition bridging can be better seen, since the goal of the algorithm is to assist in instances when the underlying traffic network is partitioned. As a result, when the input rate is low, partition bridging allows WiNDCC vehicular systems to find out about the event sooner and adjust travel routes accordingly.

Chapter 7: WiNDCC Performance with *Cache and Carry*

Message Forwarding

Thus far and in terms of WiNDCC network layer functionality, WiNDCC equipped vehicles in each of the previous experimental setups relied primarily on the fast path message forwarding scheme described in section 3.7.3. Looking back, the fast path message forwarding technique used the vehicles within the reported link and those potentially traveling into the reported link to broadcast the delay information. Therefore in the abovementioned scenarios, vehicles from each flow were responsible for both broadcasting and forwarding the traffic information about links ahead of it, to allow the vehicles behind it an opportunity to adjust travel if necessary and forward the necessary traffic information. Most importantly, this scheme was adequately able to mitigate the travel delay by taking advantage of the connectivity in which the underlying traffic network allowed, although this may not always be so.

In terms of the overall network layer functionality attributed to the WiNDCC system, another forwarding principal is vitally important to overall routing layer functionality and system efficiency. That is, the WiNDCC *cache and carry* message forwarding subcomponent described in section 3.7.5 also contributes to the delay mitigating capabilities of WiNDCC. In fact, as will be seen in the experiment performed in this chapter, sometimes traffic delay mitigation cannot effectively be achieved without the aid of background traffic deploying the *cache and carry* message forwarding to spread traffic information. As a consequence, this chapter presents a scenario in which the *cache and carry* forwarding operation is necessary to delay mitigation.

7.1 Simulation Setup

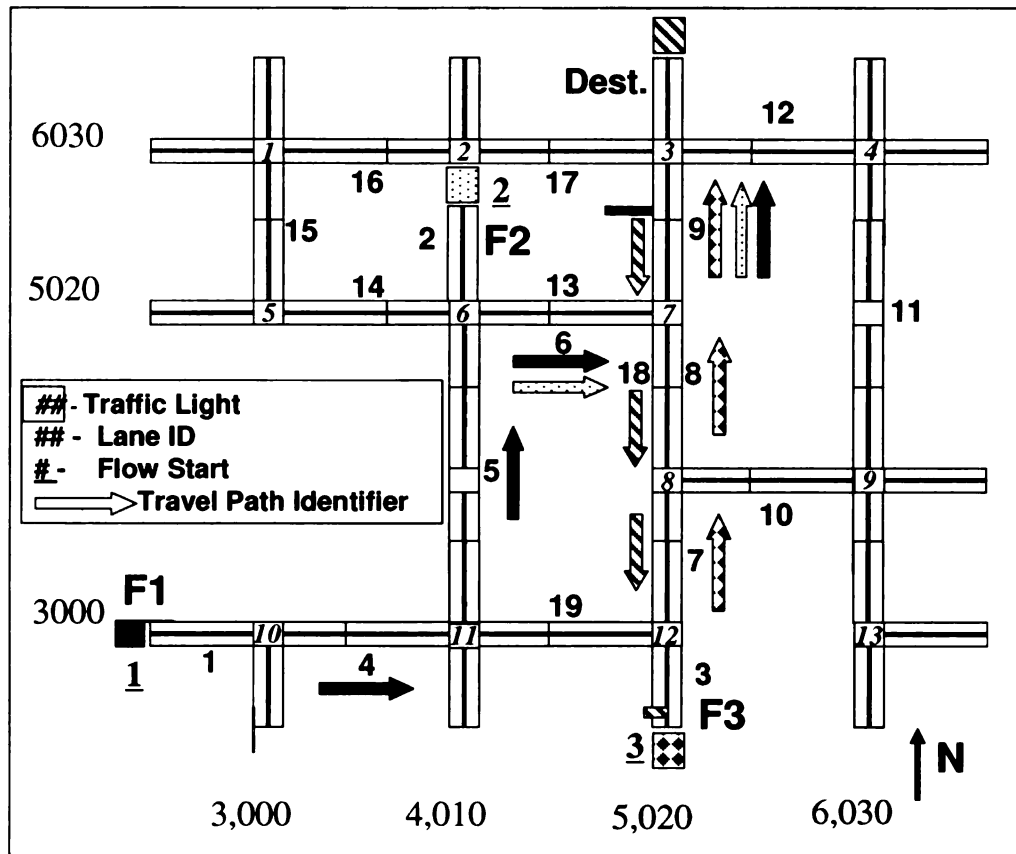


Figure 7-1: Simulated traffic network with relevant markings

| Flow ID | Number of Vehicles | Flow Start Time | Input Rate |
|------------------------------------|--------------------|-----------------|---------------------|
| 1 – Dormant Flow | 300 | 300s | .5 Vehicles/Second |
| 2 – Dormant Flow | 180 | 650s | .5 Vehicles/Second |
| 3 – Target Flow | 200 | 450s | .06 Vehicles/Second |
| Background Flow From Dest. to 3 | 250 | 80s | .1 Vehicles/Second |

Table 7-1: Experimental flow properties

The simulation setup for the scenario performed in this chapter is similar to the ones seen in the previous chapters. That is, the three flows shown in Figure 7-1 remain, with slight variation. Also, another background flow is added that will provide the *cache*

and carry functionality highlighted in this chapter. To begin understanding the new simulation setup, examine Table 7-1.

In reference to the table, the three flows are slightly modified. To begin with, flow 1 and 2 are labeled as dormant flows, signifying that these flows will not be equipped with WiNDCC or any other route guidance functionality. Therefore, they will adhere to the theoretical best case logic and use paths outlined for them in Figure 4-1, with respect to the destination. Also, flow 1 contains 300 vehicles and will become operational 300 seconds into the simulation, unlike the previous experiments. In terms of the vehicular input rate, the high entry rate is used as earlier described.

As for flow 3, it is also modified and listed in the table as the target flow. This naming is because it is the flow in which the results for this chapter are oriented. The flow will be equipped with WiNDCC functionality and will have an entry rate as mentioned in the table. This slow entry rate will make this flow unable to use WiNDCC with fast path forwarding to alleviate the travel delay it will experience due to flow 1 and 2, due to the severe partitioning between vehicles. In the results section, this will be clearly seen.

In addition, another flow is added that will implement the needed *cache and carry* functionality required to effectively alleviate the travel delay experienced by the target flow. This background flow originates from the common destination of flow 1, 2, and the target flow labeled 3; and, the destination for the vehicles is the same as the origination of the target flow. It also uses WiNDCC and uses the theoretical best path as outlined by the arrows extending from the destination as seen in Figure 4-1. Therefore, the flow will traverse the same roadways as the target flow but in the opposite direction. In terms of

the entry rate, this flow uses the low rate according to the previous experiments. Because of this rate, and since the vehicles of this flow will be the only ones using the highlighted travel links, any traffic congestion along the travel path will not be enough for the WiNDCC route computation module to guide these vehicles away from the originally computed primary path. It will be seen in the results that this flow enables delay mitigation for the target flow.

To assist with summarizing the simulation setup, a description of the data series that will be used in the results can be given. The first series is similar to the previously encountered NTCC with all flows combined. However in this case, the heading is reserved for describing the target flow performance without WiNDCC enabled. The second series is the performance of the target flow under the guidance of WiNDCC with partition bridging enabled. This result is used as a reference and proves that the target flow will need other information to achieve end to end travel delay improvement. Since the flow is partitioned, the partition bridging extension is used to achieve the best results possible. The final data series will represent the target flow performance with the WiNDCC enabled background flow in the traffic network. Results will be shown supporting the claims made thus far.

7.2 Target Flow Delay

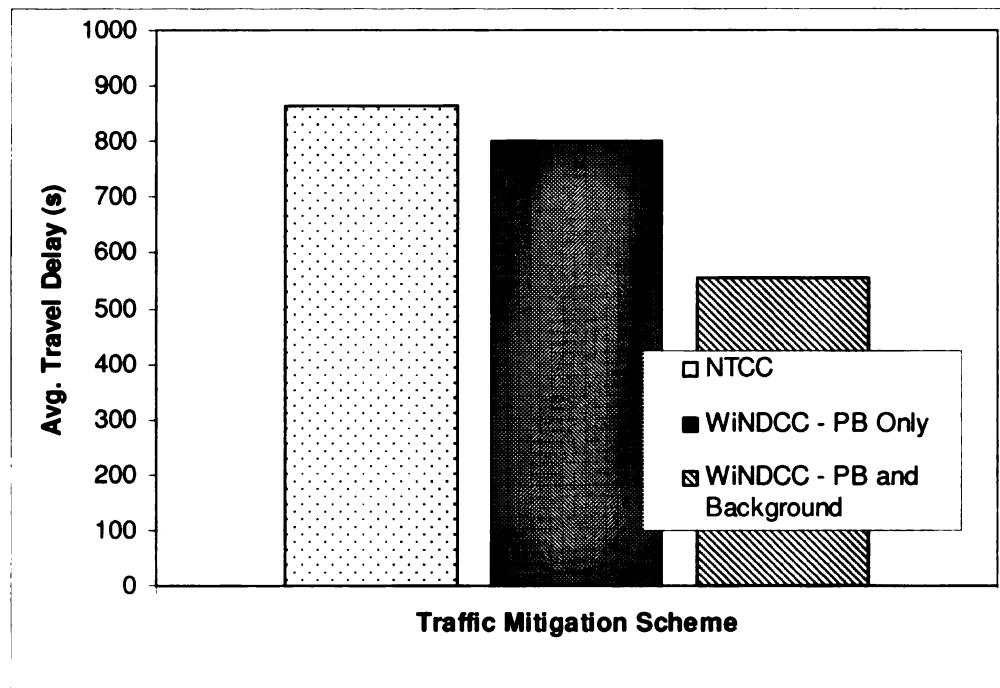


Figure 7-2: Average travel delay for target flow

First, the average delay of the target flow will be examined with regard to the abovementioned simulation scenarios and data series. The delay plot can be found in Figure 7-2. In it, it can be seen that WiNDCC with the partition bridging extension enabled is only able to partially mitigate the travel delay associated with the target flow. However, with the background flow enabled the delay is further mitigated and the advantage of the WiNDCC system can be better seen. As it will be seen when the target flow distance is examined, the reasoning behind this is quite straightforward.

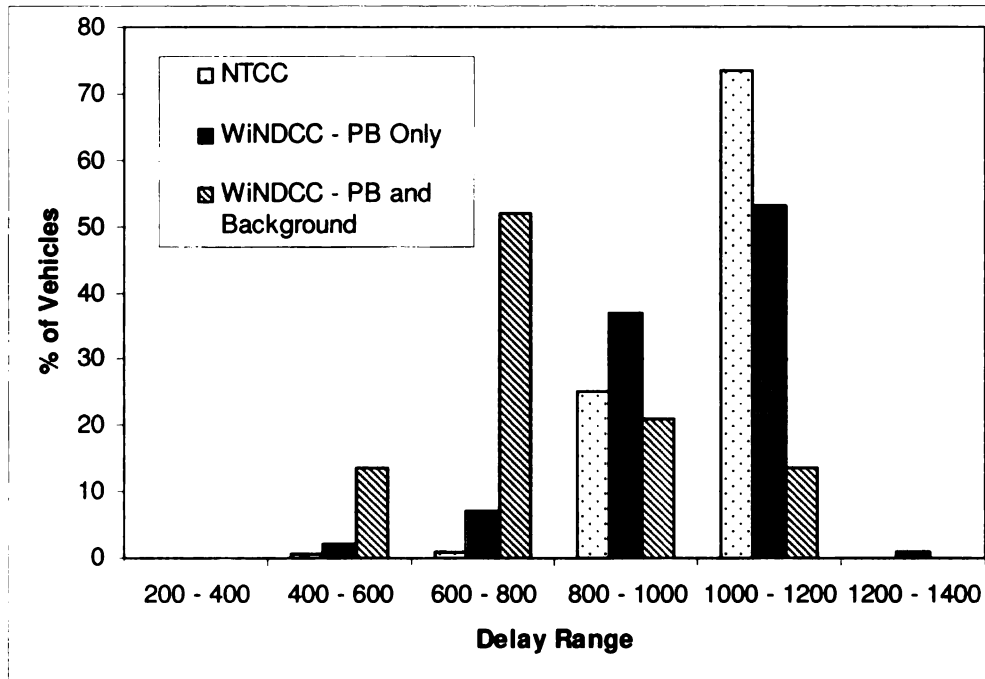


Figure 7-3: Delay distribution for target flow

As for the target flow travel delay distribution, it can be found in Figure 7-3 and adds meaning to the average delay results. That is, with partition bridging enabled the distribution is shifted to the left, a sign of delay improvement. However, one can see that the WiNDCC with background traffic shifts the distribution farther to the left, producing the superior average travel delay. Also, it can be seen that with partition bridging alone that the distribution is actually slightly worse than the NTCC case. With regard to the arguments presented in section 1.1.1, this is due to a few vehicles switching paths and experiencing a greater delay than if they would have remained on the pre computed best path. In terms of the delay vs. distance discussion, these vehicles would fall into the unjustified switching region, with respect to vehicles immediately before them that remained on the primary travel path.

7.3 Target Flow Travel Distance

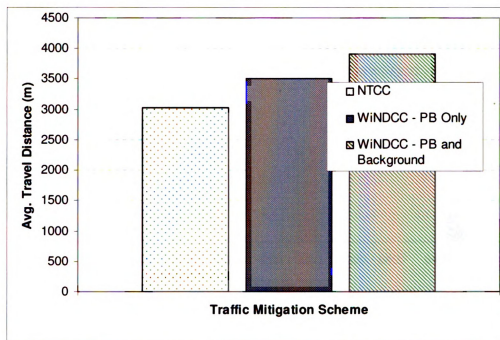


Figure 7-4: Average travel distance for target flow

By viewing the distance results for the target flow, more insight can be gained about the simulated activity. To begin with, the average travel distance for the target flow can be found in Figure 7-4. Similar to what has been discussed and seen with the presented results, with delay mitigation comes increased distance. Also, it can be seen that for the superior mitigation technique of WiNDCC with background traffic flow, the average travel distance is the highest. To understand why and put into better perspective the results presented in this chapter, consider the distance distribution which allows one to understand the actual travel paths taken by vehicles.

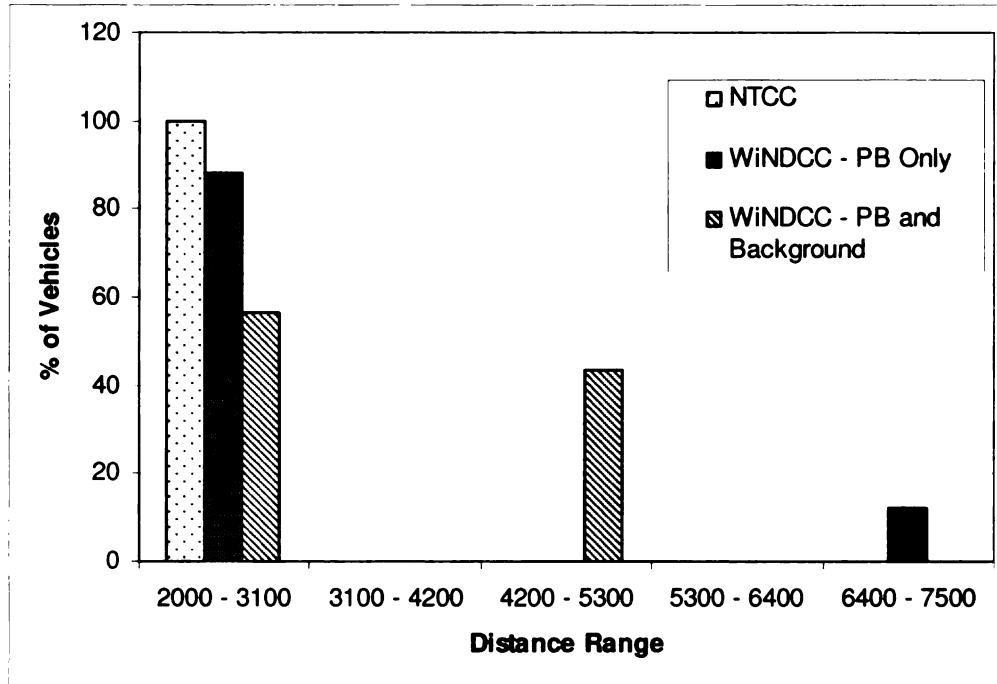


Figure 7-5: Distance distribution for target flow

The distance distribution is found in Figure 7-5. By considering it, one can see that congestion corrected WiNDCC vehicles with partition bridging enabled take a longer path to reach the destination. This is a result of those vehicles finding about the congestion in the slowed link later than those WiNDCC enabled vehicles when the background flow is added. Therefore, they take a longer path to try and avoid the slowed link, by turning left and intersection 7 and proceeding to the destination. In terms of the unjustified switching highlighted by the delay distribution, this reroute is responsible for those findings. However with the background flow enabled, WiNDCC equipped vehicles are notified about the congestion in the slowed link between intersections 12 and 8 by the WiNDCC equipped background flow, which results in them taking a shorter and more delay efficient path to the destination. This is also verified by the distance distribution.

Chapter 8: Performance of WiNDCC-enabling Wireless

Network

Thus far, all of the performance measures have been in terms of the delay mitigation goals of WiNDCC. Although the results prove that WiNDCC has potential within the realms of route guidance mechanisms, results have not been presented to verify or examine the wireless networking principles WiNDCC is built upon. It is important to do so, since within the WiNDCC design there are several nuances intended to enhance the wireless networking capabilities of the system and maintain the health and effectiveness of the wireless channel. Also, the overall research contributions of the work are not only within the traffic engineering space, but there is also interest among those studying traditional and vehicular ad hoc networks, based on the infrastructure-less VANET system WiNDCC enables.

In this chapter, results are presented that reexamine some of the abovementioned simulation scenarios from Chapter 5 and highlight some of the application and network layer functions of the system. Results will be shown that will give the reader an understanding about WiNDCC performance, from a wireless networking perspective.

8.1 Simulation Setup

In terms of the simulation setup, the wireless network oriented results will come from the simulation runs responsible for the majority of the results in Chapter 5. Like those simulations, the WiNDCC specific system parameter of ICI is set at .25, and the traffic input rate is set to the high quantity. Therefore, the simulation setup presented in this chapter mimics the one responsible for the results from Figure 5-2 through Figure

5-16. As for the results presented in this chapter, a brief description regarding the relevancy and any simulation changes required to gather the numbers for the specific quantity will be given, along with the graphical representation.

8.2 Network Overhead

In terms of the wireless network overhead associated with the WiNDCC system, the generation and forwarding paradigms aim to reduce the amount of packets sent over the broadcast medium while maintaining the traffic delay mitigating capabilities of the system. In this section, the results relate to the packet generation associated with WiNDCC under various protocol settings. In specific and as was seen in Figure 5-17 when the average end to end delay was examined, the ICI will be adjusted and the corresponding wireless network overhead values will be recorded.

8.2.1 Generated Delay Packets

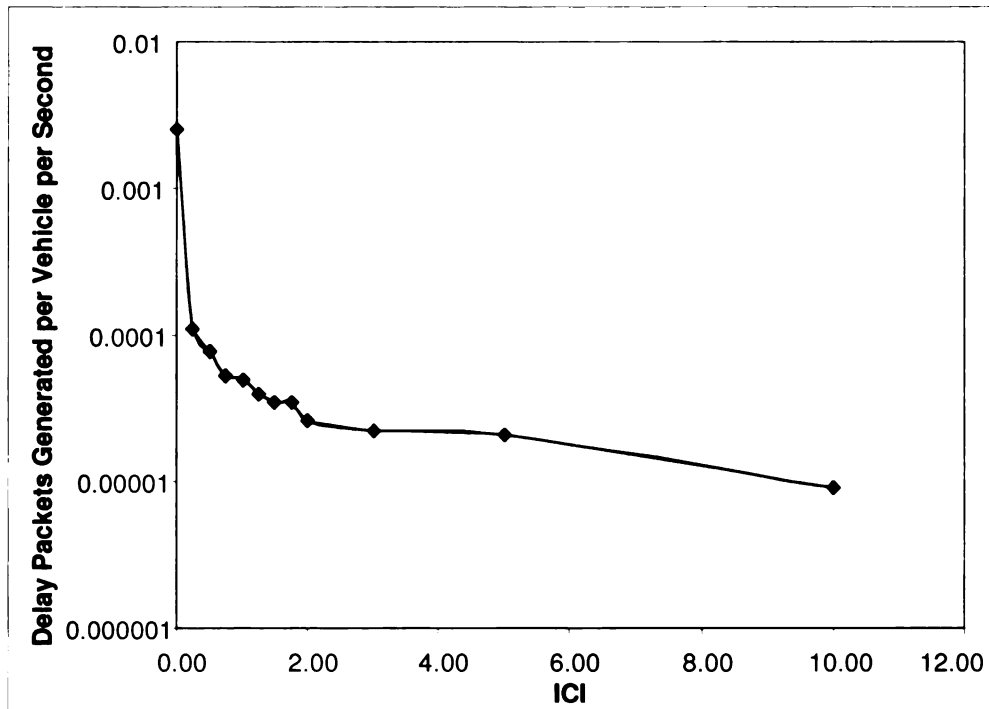


Figure 8-1: Delay packet generation

With regard to the generation scheme primarily responsible for the delay extractions used within the WiNDCC framework, the ICI determines the when to broadcast messages. To understand how this term affects the total number of delay extractions for the abovementioned simulation scenarios, examine Figure 8-1. On the x axis is the ICI value and the y axis is a logarithmic representation of the delay packets generated per second per vehicle. In the diagram it can be seen that as the ICI increases, the amount of delay extractions is decreased. This is a straightforward result of the ICI design philosophy. Also, the point where ICI is equal to 0.00 is not WiNDCC, but instead this represents a simulation run where each vehicle broadcasts its delay after exiting each link. This point is included to verify the operational aspects of the ICI. That is, since in Figure 5-17 the delay for this data point is very similar to when the ICI is

equal to .25, it can be seen that the filtering associated with the ICI and link exit routine does not adversely affect the delay mitigating capabilities of the system. The 0.00 ICI point of Figure 8-1 shows its affect, since it is much greater than that of any ICI assisted data values. This further proves that there is not a need to broadcast information in this manner, from a travel delay or wireless networking perspective.

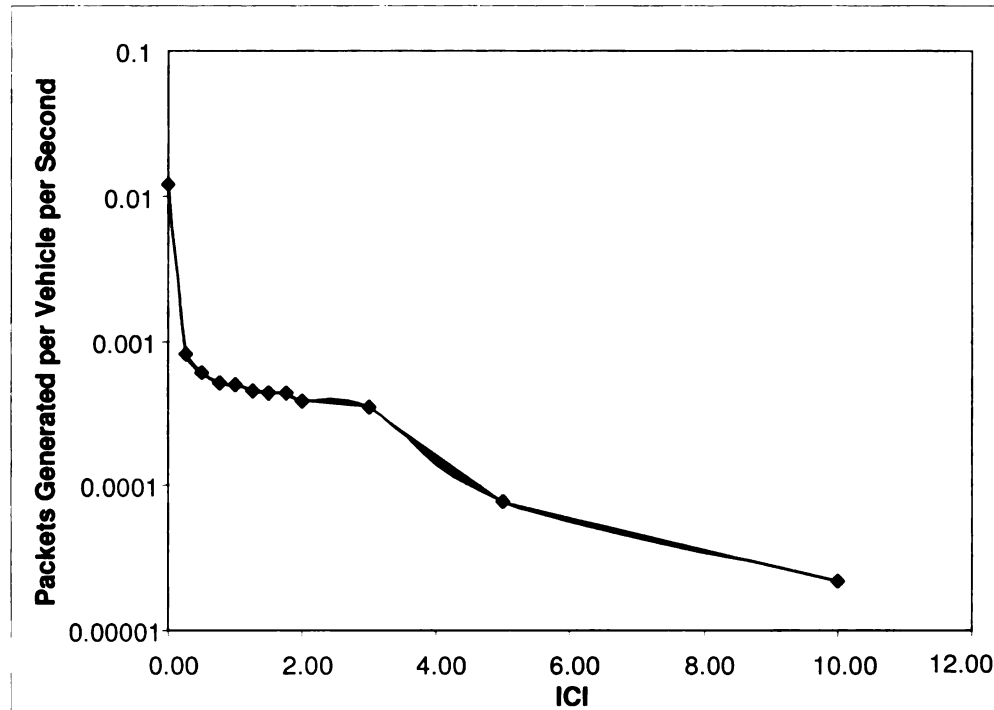


Figure 8-2: Total packet generation

In terms of the overall amount of packets generated according to ICI, this result can be seen in Figure 8-2. To clarify, the data includes all packets sent during the simulation time, both delay extractions and forwards. Therefore, the numbers exhibit the same trend as the generation numbers. The main difference is that the numbers are larger than previously seen. This result is expected, since in order for a WiNDCC device to forward a packet the data must first be generated.

8.3 Fast Forwarding Benefits

During the initial activities of the WiNDCC network layer operation, the fast forwarding scheme attempts to broadcast a packet. This protocol looks to move delay messages as fast as possible. In this section, a result is presented that highlights the importance of such activity to WiNDCC operation. A look at the WiNDCC inspired end to end traffic delay without fast forwarding will be given to show this. When fast forwarding is not used, a randomized value is chosen in between 75% and 95% of the ADI for a vehicle at packet reception time. This value is used in the place of the distance based back off time found within the fast forwarding algorithm.

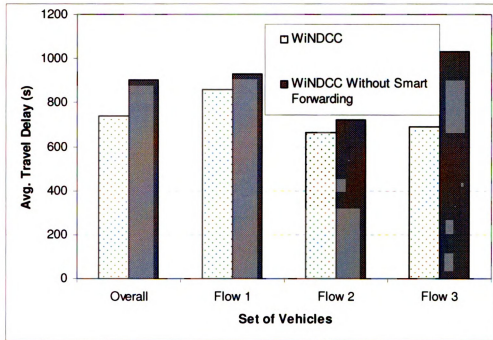


Figure 8-3: Fast forwarding travel delay comparison

In Figure 8-3 the overall and per flow end to end travel delay is shown with fast forwarding equipped and with the previously mentioned randomized forwarding. It can be seen that the overall and per flow traffic delay is increased due to the elimination of the fast forwarding scheme.

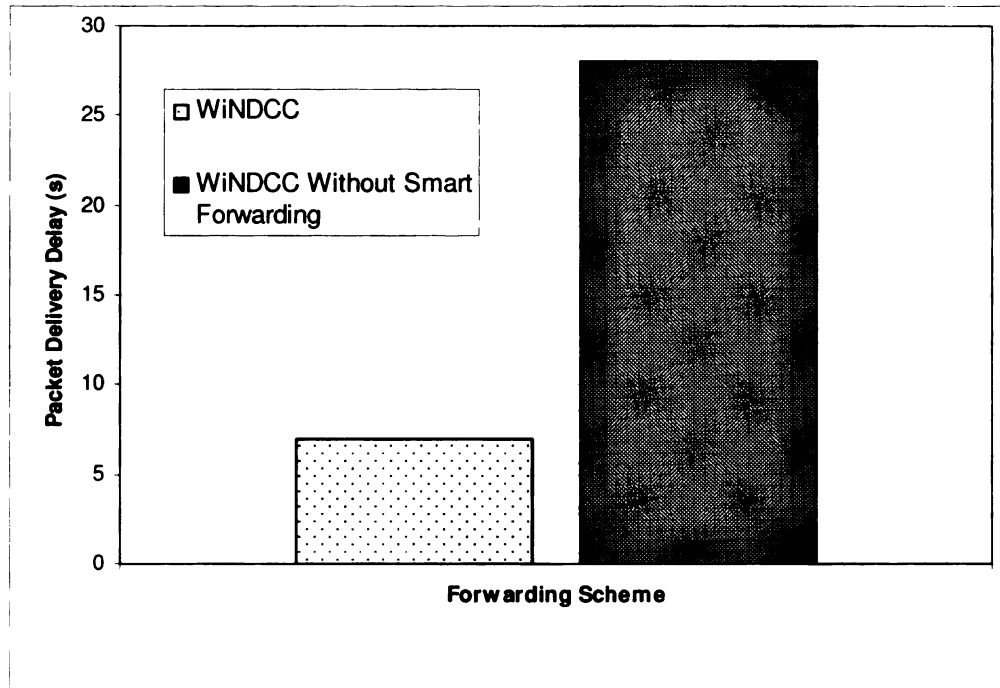


Figure 8-4: Fast forwarding packet delivery delay comparison

To understand why the delay is worsened, Figure 8-4 is included. It shows the packet delivery delay associated with any generated packet during the simulation time. To clarify, a packet is considered to be delivered when it reaches a point where the network is portioned. It can be seen that the delay is increased when fast forwarding is eliminated. Therefore, vehicles learn about delay messages later than they would with smart forwarding equipped. This explains the change in travel delay when the randomized forwarding is introduced.

8.4 WiNDCC Performance with Varying Packet Error Rate

In the wireless networking domain, packet error rate is used to understand how a mechanism will perform under less than ideal circumstances. This is done because under normal operation a wireless radio device will not always successfully receive a particular transmission, even if it is within the reception range of the sender. A random number, with respect to the desired packet error rate, is used to determine if a packet will be dropped according to this consideration.

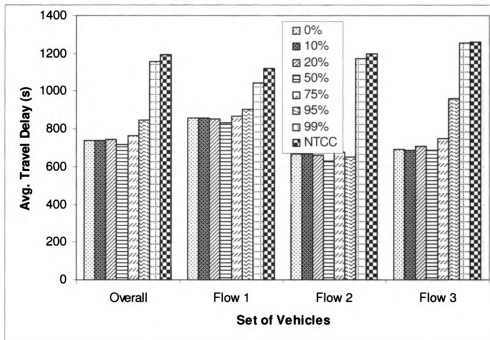


Figure 8-5: Travel delay with varying packet error rates

In Figure 8-5, the WiNDCC delay response according to various packet error rates is seen. The mechanism fairs well against packet error rate, not exhibiting degradation until about 75% of packets are dropped. This is because WiNDCC encourages vehicles to send multiple delay messages about a link, especially if it is becoming more congested. Therefore, a vehicle is eventually able to learn about a particular roadway delay, even if it has dropped one or more of the earlier messages about a link. This of course depends on the underlying network topology, which in this case is fairly connected since the experiments use the fastest traffic input rate. As a consequence, the WiNDCC enabled vehicular devices are still able to receive information and make travel decisions after information is received in an adequate amount of time.

8.5 WiNDCC Performance with Varying Penetration Rate

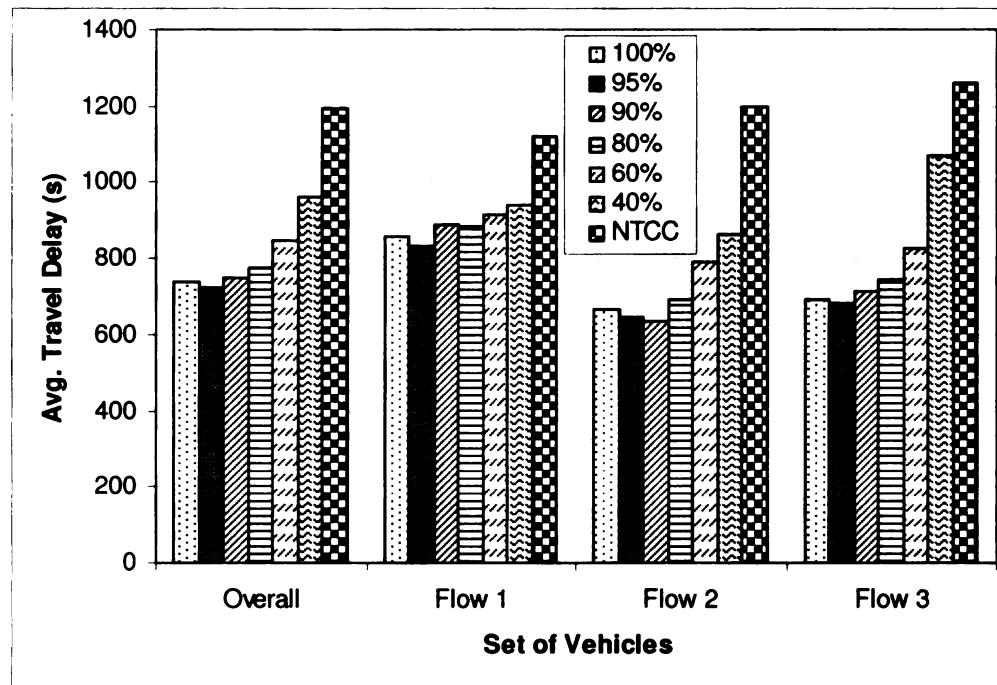


Figure 8-6: Travel delay with varying penetration rates

When implementing protocols and standards within the VANET domain, vehicular penetration rate is very important. That is, at the onset of deploying a VANET system, every vehicle on the road will not be equipped. Therefore, determining protocol responsiveness according to penetration rate is needed. Figure 8-6, gives an idea of this with respect to WiNDCC and the average end to end travel delay experienced by vehicles. As is expected when considering the limiting effects of penetration rate, it can be seen as less vehicles are made WiNDCC able, the end to end delay becomes worsened. This is expected, since fewer equipped vehicles means more drivers will remain on the pre computed best paths within the traffic network. However, these paths are congested, resulting in an increase in travel delay.

Chapter 9: Conclusions and Future Work

9.1 Conclusions

In this thesis, a completely distributed, infrastructure free, broadcast oriented, vehicular navigation framework was developed and evaluated via simulation study, called Wireless Network Enabled Distributed Congestion Control or WiNDCC. The system and the corresponding specifications are contained within the realms of the Vehicular Ad Hoc Network or VANET. In short, the primary goal of the system is to broadcast travel link delay information to the other WiNDCC enabled devices that need them, in a fast and efficient manner. From an architectural perspective, the protocols combining to form the WiNDCC paradigm reside within the application and network layers, particular to the typical wireless networking protocol stack.

At the application layer, algorithmic activity includes the generation of delay messages and the routine responsible for determining what network layer subcomponents to use for received delay messages. As for the delay generation tasks, two different routines were used to handle traffic congestion issues; the first is invoked when links are moving slowly, and the second is used to detect a stopped travel link and broadcast the information about it. In both cases, the primary goal of the generation scheme is to keep the network aware of the traffic information on a certain link, while also aiming to not over broadcast information from that link. Therefore, the system specification contains several nuances particular to this goal. As for the delay packet reception module, it is responsible for comparing the geographic positions of the sending and receiving nodes to determine which of the two network layer message forwarding policies to use for a message.

At the routing or network layer, the goal is to rebroadcast the received delay messages according to the instructions it receives from the application layer packet reception module. The receive module actually initiates the network layer operations by deciding which of the two WiNDCC forwarding paradigms will be used to broadcast a packet. The first network layer subcomponent uses the vehicles entering the link being reported by the delay message to forward the packet fast and efficiently, to other vehicles that could potentially enter that link. The primary component of this forwarding technique, called fast forwarding, is a distance based backoff timer that aims to forward packets as far as possible, with a minimal number of transmissions. This method is more successful if the underlying traffic network topology is dense and fairly connected. However during time when this is not so and the underlying vehicular network topology is very partitioned, the second network layer subcomponent can be enlisted to ensure that information is still able to be broadcast around the traffic network. That is, the *cache and carry* forwarding method uses the vehicles who have received a delay message, to carry it to other areas of the topology that could contain vehicles that can make use of the information. This method helps when the fast forwarding message paradigm is unable to deliver delay messages to certain geographical areas.

Finally, the received information about the traffic network in which a WiNDCC enabled vehicle is traveling is used within its route computation function to provide travel decisions the revised travel decisions to drivers, according to the amount delay encountered on its currently selected travel route. This component completes the sensing and reaction loop that WiNDCC enables, by allowing vehicles to use the traffic information.

This work provides simulation examples that use a macro vehicular simulator, designed and implemented as part of the work required to complete this thesis, to test the effectiveness of the WiNDCC system against various traffic congestion issues. The results show that WiNDCC enabled vehicles can avoid and help mitigate traffic delay by utilizing the roadway network for alternate paths.

9.2 Future Work

Future work concerning the WiNDCC system includes a few different tasks, each intending on understanding the effectiveness of the WiNDCC system in more realistic traffic environments.

9.2.1 Simulation and Algorithmic Fine Tuning

Still in terms of the simulation phases of system design, WiNDCC should be tested with a more realistic traffic simulator to understand how it performs. As a consequence, algorithmic nuances of WiNDCC will need to be implemented. For example, slight changes or additions will be needed to deal with multiple lanes of traffic and to handle turning lanes. Also in this simulation study, the delay mitigating properties associated with the mechanism should be explored, along with an examination of the wireless networking performance. In addition, the algorithmic components of WiNDCC can begin to be tailored in terms of a unique traffic environment.

9.2.2 Lower Layer Considerations

According to the WiNDCC system designed for this thesis, considerations were not given in terms of the layers lower than the network. However as vehicular densities increase, there may prove to be a need for MAC or physical layer assistance, to maintain

the sanity of the broadcast mechanism. Therefore, some cognitive radio or channel aware lower layer designs can be hinged to improve performance.

9.2.3 Topology Specific WiNDCC Parameterization

In terms of a real world WiNDCC implementation within a particular geographic region, it may be useful to adjust certain system parameters such as ICI, partition bridging, and DET on a link by link, time, or travel event basis. This system enhancement could prove to be the starting point for implementing real time or pre planned system operator goals within the WiNDCC system. Another, topology specific aspect that could be examined is using the data broadcast by WiNDCC devices to control traffic lights, adding another aspect to WiNDCC oriented traffic choreography.

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