AN ADAPTIVE STRATEGY FOR PROVIDING DYNAMIC ROUTE GUIDANCE UNDER NON-RECURRENT TRAFFIC CONGESTION

by

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(ABSTRACT)

Traffic congestion on urban road networks has been recognized as one of the most serious problems with which modern cities are confronted. It is generally anticipated that Dynamic Route Guidance Systems (DRGS) will play an important role in reducing urban traffic congestion and improving traffic flows and safety. One of the most critical issues in designing these systems is in the development of optimal routing strategies that would maximize the benefits to overall system as well as individual users.

Infrastructure based DRGS have advantage of pursuing system optimal routing strategy, which is more essential under abnormal traffic conditions such as non-recurrent congestion and natural disaster. However user compliance could be a problem under such a strategy, particularly when some of equipped drivers are urged not to choose minimum travel time path for the sake of improving the total network travel time. On the other hand, In-vehicle based DRGS can utilize the user-specified route selection criteria to avoid “Braess Paradox” under normal traffic conditions. However, it may be of little use under abnormal traffic conditions and high DRGS market penetration.
In conducting the comparative analysis between system optimal strategy and user equilibrium strategy, significant differences were found within the mid-range traffic demand. The maximum total travel time difference occurs when the level of traffic demand is half of the system capacity. At this point, system optimal route guidance strategy can save more than 11% of the total travel time of user equilibrium route guidance strategy.

The research proposes an adaptive routing strategy as an efficient dynamic route guidance under non-recurrent traffic congestion. Computation results show that there is no need to implement system optimal routing strategy at the initial stage of the incident. However, it is critical to use system optimal routing strategy as freeway and arterial are getting congested and the queue delay in freeway increases.

The adaptive routing strategy is evaluated using Traffic simulation model, INTEGRATION. According to simulation results using an ideal network, the travel time saving ratio is maximum when both arterial and freeway have normal traffic demand under incident. In case of a realistic network, the adaptive routing strategy also proved to save the total travel time between 3% to 10% over the traditional user equilibrium routing strategy. The reduction of total travel time increases as the incident duration increases. Consequently, it is concluded that the adaptive routing strategy for DRGS is more efficient than using user equilibrium routing strategy alone.
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1.1 Background

Traffic congestion on urban road networks has been recognized as one of the most serious problems with which modern cities are confronted. It is a widespread belief that the expansion of physical capacities of transportation facilities is not a proper solution considering the cost and environmental issues regarding road construction. Hence, transportation engineers have been searching for enhanced traffic management schemes which utilize existing facilities such as Urban Traffic Control Systems (UTCS) and Freeway Traffic Control Systems (FTMS).

However, as these systems reach maturity, the potential for future improvements in traffic flow through improved traffic control has begun to reach an asymptotic limit. (Van Aerde, 1990) Consequently, new type of traffic management approach must be found to handle the urban traffic congestion.

In this context, Intelligent Transportation Systems (ITS), a technology based on the recent and remarkable development in computer, communications and general information technologies is generally expected to be the most promising solution to traffic congestion problems. The technology has grown rapidly since the passage of the Intermodal Surface Transportation Efficiency Act in 1992. ITS has been divided into five major functional areas. Among them, Advanced Traveler Information System (ATIS)
utilizes the above mentioned technologies to collect, analyze, communicate and present information to assist surface transportation travelers in moving from a starting location (origin) to their desired destination. Especially, as a major component of ATIS, Dynamic Route Guidance System (DRGS) is seen as a powerful user service in ITS.

According to recent studies, a certain percentage of urban trips are planned irrationally and result in unnecessary delays. (Jeffery, 1987) DRGS has the potential of resolving these problems by providing driver with optimal routing to reach their destination based upon dynamic real time information. Therefore, it is generally anticipated that DRGS will play an important role in reducing urban traffic congestion and improving traffic flows and safety.

1.2. Problem Statement

Development of new technologies for the solution of any problem requires a detailed examination of all the practical issues. For the successful implementation of a DRGS, three critical issues should be considered. These issues include system architecture, routing strategy and evaluation of the DRGS benefits. Each of these issues has been briefly summarized in the following sections.

1.2.1. System Architecture

First of all, how the functions involved in route planning are distributed between the vehicles and a Traffic Management Center (TMC) is an overriding issue from the system
architectural point of view. In the TMC based system, which is infrastructure-based, the route-planning function is performed centrally by a computer system located at a TMC, while the in-vehicle based system uses a digital map stored on a computer system in the vehicle for its own routing. Therefore, the system architecture of dynamic route guidance system is directly connected with its routing strategy. The research will compare these two alternative system architecture with their advantages and disadvantages.

1.2.2. Routing Strategy

One of the most critical issues in DRGS is to develop optimal routing strategies that maximize the benefits to overall system and users while improving traffic stability in the network. The strategy has two competing perspectives: users perspective vs. operator perspective.

From a system operator's point of view, they are mainly interested in moving as many people as possible in a given time period. Practically, system operators consider what routes drivers should use, to minimize the overall travel time to all drivers, rather than letting the drivers simply select routes which minimize their own individual travel time. Theoretically, these routing strategies can be described as system optimal and user optimal respectively. The system optimal strategy has been considered for transportation of military supplies or for a railroad by central authority for the minimization of the total cost over the whole network. Now with the advent of DRGS,
This strategy may also be used for general network to make the most of available capacities in the network.

On the other hand, it is obvious that system users are interested in reaching their destination quickly and safely. Especially, when the congestion occurs in an urban transportation network, the main concern of DRGS is to provide individual driver with fast and safe routing advice toward his or her destination for the user equilibrium status.

However, both objectives often can’t be simultaneously satisfied. While the system optimal strategy has the advantage of saving a certain amount of total system travel time, the motorists might not comply. This is because system optimal routing may not recommend the best route for each individual driver.

Furthermore, if user equilibrium strategy provides all the guided drivers with the same minimum travel time path information, it is evident that the guided vehicle will concentrate at a link with a relatively low impedance and create congestion on that link.

Theoretically, we can call this as “Braess Paradox” (Braess, 1968) With low market penetrations, the guided vehicles are too few to cause new congestion. However, in case of high market penetration of DRGS, it is envisaged that the phenomenon will spread out to the whole road network. (Kan Chen, 1991)

Consequently, careful consideration should be given to adopting DRGS routing strategies. The research proposes an adaptive strategy for providing dynamic route
guidance which compromise both objectives and ultimately pursue system optimal network status.

1.2.3. DRGS Benefits Evaluation

Lastly, the usefulness of dynamic route guidance system can be determined by evaluating its potential benefits. Quantitative estimates of the potential benefits for different network conditions, traffic patterns, and the level of market penetration needs to be performed to select the optimal strategies for DRGS.

In particular, it is generally believed that DRGS will be more beneficial when the non-recurrent congestion caused by accidents or roadwork occurs. It is reasonable to believe that under normal traffic conditions, only a few drivers need to re-route themselves to keep the equilibrium state in the network; but under abnormal traffic conditions like non-recurrent traffic congestion, most of the drivers will need the DRGS re-routing information to settle the disequilibrium status.

This research will present the quantitative evaluation of DRGS benefits with the proposed strategy under non-recurrent congestion using a simulation model. Figure 1.1 illustrates the relationship among the three critical issues and implementation of DRGS.
Figure 1.1  Block diagram of the relationship among the three critical issues for DRGS implementation
1.3 Objectives of the Research

The goal of the research is to develop an effective and efficient strategy for providing dynamic route guidance under non-recurrent congestion. The research will provide a systematic evaluation of the DRGS routing strategies in the idealistic and realistic networks using simulation model analysis.

To fulfill the final research goal, the following objectives have been defined:

- Study the various system architectures of existing Dynamic Route Guidance System.
- Perform the comparative analysis of DRGS architectures between infrastructure based system and In-vehicle based system.
- Study simulation technique for evaluating DRGS benefits.
- Study the theoretical viewpoint of the two alternative routing strategies: system optimal vs. user optimal.
- Develop effective and efficient Dynamic Routing Algorithms to pursue system optimal and user optimal with the consideration of the state of the network.
- Evaluate the routing strategies for DRGS by their benefits using integrated traffic simulation model.

The optimal routing strategies for DRGS will be evaluated by following features:

- Network Configurations
  - idealized network
  - realistic network (I-66)
• The severity of non-recurrent congestion
  • Incident duration
  • Capacity reduction by incident

• Network condition
  • Freeway and arterial Traffic demands
  • Freeway and arterial link capacities

1.4 Organization of the Dissertation

The dissertation is organized as follows: Chapter 2 introduces the existing dynamic route guidance systems, system architecture and evaluation methodologies through an extensive literature review. Chapter 3 explains the comparison of system architectures and routing strategies of dynamic route guidance system under various network configurations. The methodology for estimating incident delay using deterministic queueing model is presented in Chapter 4. The chapter also proposes an adaptive strategy for providing dynamic route guidance under non-recurrent congestion. In Chapter 5, the proposed strategy is evaluated by INTEGRATION, an integrated traffic network simulation model. Finally Chapter 6 summarizes the dissertation and suggests further research.
2.1 Introduction

During the last several decades, Dynamic Route Guidance System has been drawn world-wide attentions as a strategic tool for reducing urban traffic congestion especially in the United States, Europe, and Japan. The United States once led the world in developing DRGS technologies by introducing Electronic Route Guidance System (ERGS) in the late 1960's and early 1970's. However a operational experiment in Washington D.C. was abandoned by Congress owing to the problems such as the timing of the need, the cost and the technology in 1971. (IVHS America, 1992) Thereafter Europe and Japan have mainly progressed the technologies to cope with their traffic environments.

In the mid 1980's, California Department of Transportation (CALTRAN) reactivated the research on this area to overcome growing urban traffic congestion in US. It became a motivation for US to join the development of DRGS more positively.

The first section of this chapter describes the world-wide DRGS's by their system architecture. The second section discusses the theoretical approach of routing strategies for DRGS and DRGS benefit evaluation. Finally, the overview of the methodologies for evaluating DRGS routing strategies and benefits is presented.
2.2 System Architecture

DRGS can be categorized into two alternative system architecture; in-vehicle-based system and infrastructure based system. The basic difference between the two lies in where the route-planning function is carried out: decentralized in each participating vehicle or centralized on an infrastructure-based Traffic Management Center (TMC). It should be noted that DRGS architecture is very important in that DRGS routing strategies will be derived from its system architectures.

Generally European DRGS architecture has the features of infrastructure-based system architecture. The following DRGS’s are representative projects currently implemented or under developing in Europe.

- ALI SCOUT (EURO-SCOUT) - Germany
- AUTOGUIDE and ROMANSE - England
- INF-FLUX - France

On the other hand, In-vehicle-based system architecture seems to be preferred by Japan as follows;

- AMTICS
- RACS
- VICS
Recently U.S.DOT has initiated the National ITS architecture deployment program with the aim of developing an architecture by mid-1996. The currently developed major DRGS and the proposed architectures by ITS America are as followed:

- PATH FiNDER
- ADVANCE
- TRAVTEK
- Huges Architecture
- Loral Architecture
- Rockwell Architecture
- Westinghouse Architecture

2.2.1. Infrastructure Based System

In the infrastructure-based system, the route-planning function is performed by a computer system located at a traffic control center. This computer stores the map of local link network in the area covered by system. It also stores current road link travel times based upon road status information and actual link travel times reported by vehicles equipped with the navigation system. The central computer selects best route based on actual road status and traffic data, and generate guidance instructions for each participating vehicle to complete its trip. These guidance instructions are transmitted or broadcast to the vehicles by roadside infrastructure such as beacons and wireless communication system.

Most of the DRGS's developed in Europe has the features of Infrastructure based system architecture. Romuld (1991) provided summaries of each system features as follows:
ALI-SCOUT/LISB (Germany)

The system is a dynamic route guidance system that uses infrared transmitters and receivers to transfer navigation information between roadside beacons and on-board displays in appropriately equipped vehicles. The vehicles receive routing information from a centrally located traffic guidance computer when passing infrared communications beacons installed at selected traffic signal lights and other strategic locations.

The received information consists of a route tree giving the best routes based on current traffic conditions for traveling from the beacon location toward various destination zones. The on-board equipment selects from the route tree according to the destination input by the driver, and issue route guidance instructions along the way by means of a simplified graphic display and synthesized voice. Navigation between beacon locations is accomplished by dead-reckoning with map-matching, and travel times for road links along the route are communicated to the beacons to augment the traffic information database of the central traffic guidance computer.

Guidance recommendation differ fundamentally from other kinds of information such as weather reports, stock exchanges report since they only apply to one point at a time or to one route. This is why it is not advantageous to broadcast traffic information through wide-range transmitting stations over wide area.

Dynamic route guidance information can only be as good as the guidance computer’s knowledge of the actual and foreseeable traffic in the near future. It cannot obtain adequately up-to-date information from the police, from traffic authorities or from
detectors installed in the road network. This is why there is a trend toward equipping vehicles themselves as collectors of traffic data. That is to say, the on-board computers can easily and economically measure journey times needed for each section of the route and waiting times spent at traffic signals. These “experienced reports” are returned when the next respective beacon is passed as payment in kind, so to speak, for good guidance recommendation.

EURO-SCOUT is the latest generation of the ALI_Scout system. Additionally it includes the ability to provide public transit and parking availability information to the driver of an equipped vehicle.

LISB (Leit and Information System in Berlin) project is testing the ALI-SCOUT system and other European country also are installing the system by different names such as ULISSE in France, Wegwijs in Netherlands.

♦ RDS-TMC (Radio Data System/Traffic Message Channel)
This is a system for disseminating traffic information by means of the designated side-band of existing FM radio broadcasts. This system is more suitable for radio traffic information services than paging or cellular system, because its two-way communication capability does not allow a full scale onboard navigation system for dynamic route guidance information services. As it stands, this technology is most likely the one to be implemented in the immediate future.
TRAFFICmaster

TRAFFICmaster is a simple, low cost, and transportable in-vehicle device for dynamic traffic information services. The system developed by private investment, has been commercially available in England. It automatically alerts drivers with up-to-the minute traffic information on freeway congestion. It uses the existing radio communication system available for paging.

AUTOGUIDE

There is widespread support for the view that the most effective form of vehicle navigation, dynamic route guidance, will be most successfully implemented using a control center and a communication infrastructure to transfer information between the control center and equipped vehicles. To prepare the way for such a system, a bilateral working party was set up by the British and German government in 1987.

They adopted AUTOGUIDE as an infrastructure-based, dynamic route guidance system, which is based on network of short-range beacons connected to a control center. All equipped vehicles passing a particular beacon at a particular time receive the same set of data, via a communications link based on infrared purses giving a high data rate (currently up to 500kb/sec). The data set includes location, map, and route data, which will have been calculated during the last 5 min at the control center, based on actual traffic conditions.

Communication with the beacons is two-way. Travel time data from fitted vehicles are transmitted anonymously to the beacons and hence to the control center; this important
function will give the control center a traffic monitoring capability of unmatched quality. As well as the ability to recalculate routes in near real-time, the system will detect and react immediately for improving traffic control quality based on advanced traffic monitoring.

♦ ROMANSE

ROMANSE (ROad Management system for Europe) is a test bed project to experiment with the multi-modal transportation systems in England. The aim of the project is to establish a comprehensive, real-time, multi-modal information center which can collect, evaluate, coordinate and disseminate both real time and forecasted information on networks and service requirements for travelers by automobile, bus ferry, and plane.

The Siemens’ EURO-SCOUT central computer will be used with appropriate models to provide route recommendations. Subject travelers will be provided with strategic trip planning and tactic a enroute information services through various dissemination tools including radio broadcast, (RDS-TMC and local radio), other broadcast (telex, cable TV, videotext), variable message signs (adviscry route advice, parking guidance and special needs such as bridge closure) and passenger information (on-board buses, trains and ferries at terminals. (Yim, 1993)

♦ INF-FLUX

The INF-FLUX project, in Paris, is planned to use RDS (Radio Data System) to send traffic flow information to drivers. RDS is a system for transmitting data by means of a data channel on the sidebands of existing FM radio broadcasts. Linked with ULISSE, the intention is to install infrared beacons in Paris, which will provide a detailed traffic
monitoring system. A special terminal has been designed, which will allow a driver to input some details of his preferred route and of possible alternatives; using the RDS channel the terminal will be updated to show which of the selected routes are suffering from congestion.

The idea behind this system is that French drivers will not readily take to the ALI-SCOUT system because it does not offer an explanation of the recommended route, nor does it offer an alternative. INF-FLUX will allow the driver to make his own choice of route. This approach is unlikely to achieve the same level of benefits that a true route guidance system offers, although the in-vehicle equipment might be less expensive.

◆ PROMETHEUS (PROgrammeme for European Traffic with Highest Efficiency and Unprecedented Safety)

PROMETHEUS is one of two major European IVHS program contributing to ATIS. It will develop a European-wide traffic management and control system using three major levels of information transfer or communication-intelligent driver aids on-board the vehicle, communication networks between vehicles, and communication and information systems that link vehicle and roadside facilities. It is coordinating work on a “dual-mode” route guidance system which will function as both an autonomous system and with infrastructure support where available.

◆ DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe)

DRIVE is the other major European IVHS program. The purpose is to find the ways to alleviate road transportation problems through the application of advanced information
and telecommunications technology. SOCRATES (System Of Cellular Radio for Traffic Efficiency and Safety) is the largest DRIVE project, which is to use cellular radio for widespread two-way communication between vehicles and control centers. They will use specific frequencies from pan-European GSM system to broadcast, in a same way to ALI-SCOUT/Autoguide, the same data set to all equipped vehicles within specific cells. A multiple-access protocol will provide for transmission back to the control center from equipped vehicles.

PROMETHEUS and DRIVE share similar objectives, to support drivers by optimizing road utilization through the application of the latest information and telecommunication technologies, but the research focuses are quite different. The research interest of PROMETHEUS is in development of vehicle communication and safety system while DRIVE is focused on the community issues related to traveler behavior, standardization, and technology deployment.

2.2.2. In-Vehicle Based System

In this system, route planning is done using a digital map stored on a computer system in a vehicle. An on-board navigation system, based on GPS or other in-vehicle location system, automatically determines and displays the location of the vehicle. When a destination is specified, the PC-like route guidance computer can select the best route and generate guidance instructions to complete the trip. The guiding may be done with graphics on the computer screen or on a "head-up" display on the windshield, or by voice commands.
Figure 2.1 illustrate a prototype of the in-vehicle based DRGS architecture. The destination might be an address of the name of a business listed in a computer’s database. Real-time traffic information is broadcast by the TMC and used by this computer to re-route the vehicle around congestion. In-vehicle processor would be provided Dynamic Traffic Information such as link travel times, incident, and other temporary restrictions from the TMC for route selection.

2.2.2.1. United States

♦ PATHFINDER

Pathfinder is the first IVHS operational field test in the United States. PATHFINDER is a field test of in-vehicle urban freeway navigation and information system in California. It provides drivers of specially equipped vehicles with navigation systems, real-time traffic information, and suggested alternate route. A control center measures traffic density and vehicle speeds, and transmits congestion information to the vehicle in the form of an electronic map shown on a display screen. The system helps motorists to find the most efficient path of travels to their destination.

♦ TravTek (Jasper, 1992)

TravTek in Orlando, Florida is testing various ATIS technologies, which provide navigation, real time traffic information, route selection, route guidance and motorist information services to a fleet of 100 specially equipped rental cars. The Travtek vehicles
have two computers for navigation and route guidance respectively. A TMC transmits the traffic conditions digitally to the equipped vehicles, which in turn act as probes to supply traffic information to TMC. TravTek also testing dynamic reroute system, which is equipped in vehicle to reconfigure driving routes based on real-time traffic conditions or incidents.

♦ ADVANCE

Kiroson (1992) introduced ADVANCE as the first public/private sector partnership in North America, established to field test many aspects of dynamic route guidance, officially launched on July, 1991 in Chicago area. ADVANCE has the following key concepts of system architecture;

• Distributed intelligence (all route planning is performed in the vehicle)

• An hierarchical road network database (for higher performance in all map-related functions)

• Vehicle as traffic probe (for accumulating real-time information)

• Open (non-proprietary) RF data communication protocol and driver interface

The routing strategies of ADVANCE are as follows; The fastest route to the destination is calculated based on historical traffic patterns contained on the CD-ROM and real-time traffic data broadcast from the TIC (Traffic Information Center). The user can set up a trip
Figure 2.1 In-vehicle based dynamic route guidance system (decentralized)

(Kiroson, 1992)
with multiple destinations, and save a trip for later recall. The user can also specify detours which encourage or discourage the use of a particular road in the selection of a route. The user also elect to avoid freeway, toll ways, and particular localities. In addition to finding fastest route, the user can specify the shortest path or the route with the fewest maneuvers. These preference can be applied to all trips for a particular driver or to a particular leg of a trip.

2.2.2.2 Japan

Kawasima (1991) introduced the two major research projects on in-vehicle information system in Japan as follows;

♦ AMTICS (Advanced Mobile Traffic Information and Communication System)
At the beginning of 1987, The National Police Agency proposed a project called AMTICS with the cooperation of the Ministry of Posts and Telecommunications. AMTICS is a relatively sophisticated traffic information system and control system that transmits traffic congestion information from a traffic control center to an in-vehicle display. It has the capability to provide static and dynamic information. The system is a cellular type (3Km radius areas), two-way digital packet, multi-channel access communication system.

♦ RACS (Road/Automobile Communication System)
RACS began as one of the member-initiated research projects of HIDO (the Highway industry Development Organization) in 1984, which is under supervision of the Ministry of Construction. RACS is consists of roadside communication units (beacons), on-board
vehicle units and a system center. RACS collects and disseminate information between roadside beacon and vehicles. The system is based on the newly developed intermittent two-way digital mobile communication system using microwaves. The system functions are classified into navigation, roadside information and message systems.

The only difference in AMTICS and RACS is that communication link and in-vehicle-units are almost same. Thus efforts of integrating these two system resulted in jointed project named VICS(Vehicle Information Communication System) in 1990.

Although Japanese development of in-vehicle information system originates from CACS (Comprehensive Automobile Traffic Control System), which was a centralized type, the Interactive route guidance system by two-way communication link might not be feasible considering huge cost of constructing and operating the central facility. On the other hand since road traffic phenomena in the network are very complicated and congested especially in Tokyo, a sufficient number of alternative routes may not exist. In this respect insufficient route guidance may lead to liability problems. When the unification of AMTICS and RACS is settled, the route guidance system design will follow.

It seems that the design concept of the Japanese system will be in-vehicle based system, which is designed to calculate and determine the guided route by on-board computers. The central facility will be designed to accumulate and process the traffic data from vehicles and from the traffic control centers. The two-way communication link is inevitable in order to know on-line traffic data such as travel time of vehicles in the network. The design policy will eventually lighten the burden the central facility, and the
function of the central facility can be specified to conduct estimation and prediction of the costs necessary to calculate “optimal routes” by on-board computers.

2.2.2.3 Canada

Heti (1991) presented TravELGuide as the conceptual DRGS in Canada as follows;

TravELGuide

The Ministry of Transportation of Ontario is actively pursuing the assessment and possible development of TravELGuide, a route guidance system, that will offer most of the benefits of more advanced systems but at significantly lower cost. It is a portable computer that incorporates a digital map database, a radio receiver to collect real-time link-travel time information, a graphical and text display capability, route guidance software, synthesized voice to provide directions to the driver and appropriate user interfaces. The device does not come with or require a navigation capability for operation. The system calculates an optimal route based on driver-assigned criteria such as shortest trip, quickest trip or perhaps most scenic trip. The route calculation is based on the latest link travel time information received by the unit from the area’s traffic control center. But this is a concept. Figure 2.2 illustrate the cost/benefit of existing ATIS equipment compared with TravELGuide system.

Table 2.1 is a updated version of Heti(1991)’s table for the summary of current ATIS developments. The table is classified by its system architecture. Most of the systems have route planning and guidance function.
Figure 2.2 Cost/ Benefit of existing ATIS (Heti, 1991)
<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>Based</th>
<th>System</th>
<th>AMTICS</th>
<th>PATH-FINDER</th>
<th>TRAVEL GUIDE</th>
<th>TRAV/TEK</th>
<th>AUTOGUIDE</th>
<th>AUTOGUIDE</th>
<th>INF-FLUX</th>
<th>ALI-SCOUT</th>
<th>INF-FLUX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route Planning</td>
<td>Location/Navigat</td>
<td>Route Guidance</td>
<td>Link travel Time</td>
<td>Detailed Map</td>
<td>Other Travel Info</td>
<td>Portable</td>
<td>Demonstration</td>
<td>Communication Media</td>
<td>RDS-TMC</td>
<td>Unsequipped</td>
<td>Equipped</td>
</tr>
<tr>
<td>Freeway</td>
<td>Freeway</td>
<td>Limited</td>
<td>Limited</td>
<td>Limited</td>
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</tr>
<tr>
<td>London</td>
<td>Tokyo</td>
<td>LA</td>
<td>Toronto</td>
<td>Southampton</td>
<td>Paris</td>
<td>Berlin/London</td>
<td>Site</td>
<td>Media</td>
<td>Beacon</td>
<td>Beacon</td>
<td>Beacon</td>
</tr>
</tbody>
</table>

Table 2.1 Features of the current Dynamic Route Guidance System

- O: Equipped
- : Equipped
- Unsequipped
2.2.3. Proposed DRGS Architecture by ITS America

U.S.DOT has initiated the National ITS Architecture Development Program with the aim of developing an architecture by mid-1996. In 1993, U.S.DOT selected teams led by Hughes Aircraft, Loral, Rockwell International, and Westing House Electric to each develop and alternative ITS architecture. The summary report of ITS Architecture Development Program Phase I (ITS America, 1994), have proposed these four system architectures related with route guidance user services in road networks as follows:

- Hughes (In-vehicle Based)

Hughes architecture for ITS specifies a tag/beacon approach to vehicle-roadside Communications and that vehicles of all types are equipped with tags so that they can take advantage of the traffic advisories provided by this architecture. The route guidance vehicle contains a PC type computer which is programmed to select a route between the vehicle’s current location and a desired destination, and then to guide the driver along that route. The route selection can also be done at a TMC, but Hughes team believe that it is risky to assume that such a service would be available nationally and for that reason plus privacy issue, in-vehicle route selection is the standard. Real-time traffic information is broadcast area-wide to enable route selection programs to avoid congestion.

- Loral (Infrastructure Based)

The Loral team believes that a competitive free market is the best mechanism for allowing travelers to get the services and products that they want at the lowest prices.
To encourage a free market for the delivery of travel services, the Loral Architecture has defined a private sector Information Service Provider (ISP) subsystem with standard message interfaces to the public sector TMCs, other fixed subsystems, and their traveler clients located at home, at an office at a kiosk or in vehicle. These ISPs will compete for customers by differentiating themselves through the quality of the information which identifies “best” multimodal trips, vehicle route, ridesharing matches and so on.

- **Rockwell (infrastructure Based)**

  In the Rockwell system architecture, the Transportation Management Center (TMC) will have four subsystems; traffic and Emissions Management, Transit Management, Emergency Management, and the Travel Information Provider subsystems. Among them, the Travel Information Provider subsystem provides information and services to travelers and the media, including pre-trip and en route information, route planning with updates based on traffic conditions, incident notification, parking management, and Mayday support.

- **Westinghouse (Flexible)**

  Westinghouse system architecture seems to be eclectic and flexible in terms of route guidance user services. That is to say, the Personal Travel Service System which contains all private in-vehicle ITS equipment, one of the eight physical systems in the architecture, can provide its own route guidance with link time from the TMC, or directly pick up centrally-processed route guidance from TSC (Transportation Service Center) in the Public travel Service System of the Architecture.
2.3. DRGS Routing Strategies

2.3.1. User Optimal vs. System Optimal

Transportation Engineers have traditionally been interested in traffic assignment techniques to determine how drivers choose their routes in a network under the present or future traffic demand. There are two well-known principles which were first introduced by Wardrop (1952).

He presented following criteria for determining the distribution of traffic over alternate routes:

(i) "The journey time on all routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route."

(ii) "The average journey time is a minimum."

Wardrop compared these two as follows: "The first criterion is quite a likely one in practice, since it might be assumed that traffic will tend to settle down into an equilibrium situation in which no driver can reduce his journey time by choosing a new route.

On the other hand, the second criterion is the most efficient in the sense that it minimizes the vehicle-hours spent on the journey." The flows resulted from the equilibrium assignment based upon first criterion is called "User Optimal" and "System Optimal" is the traffic equilibrium assignment based upon second criterion. The following chapter will discuss the principles in detail as the DRGS routing strategies.
2.3.2 Anticipatory Route Guidance System (ARGS)

The most important test of DRGS is whether an individual driver with equipped vehicle can get efficient and safe routing information after non-recurrent congestion occurred. Chen and Underwood (1991) emphasized that such information should take into account not only current traffic conditions but also anticipated delay that may occur before the driver reaches his destination. They proposed “Anticipatory Route Guidance System” that provides predictive routing based not only on where the vehicles are, and have been, but also on where the vehicles are likely to be in the future.

They also suggested the critical features of the Anticipatory Route Guidance system (ARGS) as follows:

1) The predictive model must operate at a rate faster than the traffic system itself.

2) The predictive model must use the response from past traveler decisions and their impacts on the traffic system to improve the next generation of predictions. In other words, the predictive model must adapt and learn as the traveler acts on the system through time. Furthermore, the model must operate fast enough to generate predictions that can be used effectively to influence the traffic system.

Figure 2.3 and Figure 2.4 illustrates alternative framework for ARGS by system architectures. The system works as follows. The predictive model receives information from traffic monitors on the state of the actual network traffic system and the results of past controller actions.
The model uses this information to predict future states of the traffic system and transmits this information to the route controller. The individual route optimizer integrates this prediction with an assessment of traffic and the general environment to determine a desirable route and possibly a departure time on request by the traveler. Travelers makes decisions and takes actions based on multiple information sources. An understanding of driver routing behavior, including the driver's propensity comply with route guidance instructions, is essential for accurate traffic forecasting. The action of the traveler then influence the system and the cycle itself.

It can be seen that the ARGS is a extension of adaptive control strategies. The adaptive control strategies considers only the current and past state of the system. on the other hand ARGS adopts control strategies which is based upon future traffic conditions obtained by time-dependent traffic forecasting model. Nowadays various approaches including artificial intelligence, statistical approach like time-series analysis and simulation techniques have been used for forecasting future traffic conditions.
Figure 2.3 Conceptual Structure of Anticipatory Route Guidance System
(Infrastructure(TAC)-based) (Chen and Underwood, 1991)
Figure 2.4 Conceptual Structure of Anticipatory Route Guidance System (In-vehicle based) (Chen and Underwood, 1991)
2.4. Methodologies for DRGS Benefits Evaluation

2.4.1. Heuristic Approach

Van Aerde and Rakha (1989) examine the traffic engineering potential for implementing system optimized routes in Urban traffic networks using in-vehicle route guidance system. They presented a 2 route example to estimate the potential travel time savings and to predict the extent to which the traffic equilibrium would be disturbed. The theoretical solution to the system optimum routing problem is compared with a more practical heuristic approach.

They suggested two basic methods to derive system optimal assignment as follows,

1. One can exhaustively enumerate all possible routing combination and compute the total travel times for each. Consequently the optimum routing can be identified by selecting the routing with the lowest total travel time.

2. Alternatively, one can combine the total travel time equation for route 1 and route 2 and add the further constraint that the traffic volumes on route 1 and route 2 must sum up to the total demand. This equation can then be differentiated, in order to find the minimum.

However, these method are not satisfactory approach for finding system optimized routings, when more than just a few possible routes are available. Consequently a more practical method for determining System Optimum routing is desired. They suggested an incremental system optimized assignment algorithm. They include the two terms
which reflect the increase the total travel time. The first component consists of the travel time incurred by the particular vehicle, while the second consists of the increase in travel time that is imparted onto all the other vehicles, which are already on the link.

Thus by including this second delay component in the incremental assignment, they presented a method to change a User Optimum assignment to a system optimum assignment. The precision of this methodology is a function of the number of increments that are utilized, and in particular the size of the final increments, if not all increments are of the same size.

They also pointed out the benefit of going from a User Optimal routing to a system optimized routing are of course a function of the network characteristics, the level of traffic demand and the nature of travel time relationship.

2.4.2 Theoretical Approach

Kanafani and Al-deek (1991) proposed a theoretical approach to estimate the benefits from vehicle route guidance in urban networks. They assumed that route can be altered in such a way as to achieve system optimal assignment and benefits are measured by savings in total travel time when comparing this assignment with the user equilibrium, which is to occur in the absence of route guidance. A continuum approach is used to analyze an idealized corridor in which a freeway is superimposed over a dense grid of surface streets.
With some simplifying assumptions, they explored some theoretical aspects of the benefits of user equilibrium and system optimal assignment in a simplified road networks.

- **User Equilibrium Assignment**

Consider a traveler originating at point A(x, y) and destined to point B(x+L, y). Under user optimal status, the freeway path will be used when

$$2yK + L c(f) \leq LK$$  \hspace{1cm} (2.1)

where

- **K** is the constant average and marginal cost on the city street
- **L** is the trip length
- **c(f)** average travel cost function on the freeway
- **f** the freeway flow

Equating the two sides of the equation (2.1) gives the critical value \( y_1 \), which defines the user shed boundary of the freeway.

$$y_1 = \frac{L [K - c(f)]}{2K} \hspace{1cm} (2.2)$$

The flow on the freeway can be calculated by considering that all users within the shed defined by \( y_1 \) on either side of the freeway as follows;

$$f = 2 \beta L y_1 \hspace{1cm} (2.3)$$
where $\beta$ is the trip density in the vehicle trips per unit of time per unit of distance squared. Using a freeway cost function of the following standard type:

$$c(f) = t_0 \left[ 1 + (\beta \mu)^2 \right]$$  \hspace{1cm} (2.4)

where $t_0$ is the free flow travel time per unit distance on the freeway (e.g. 1 minute per mile) and $\mu$ is the capacity of the freeway. The user equilibrium flow $f_1$ and total system cost $T_1$ is calculated as follows:

$$f_1 = \frac{\mu^2}{2t_0 \beta L^2} \left[ -K + \frac{1}{\mu} (A + B)^{0.5} \right]$$  \hspace{1cm} (2.5)

in which

$$A = K^2 \mu^2$$

$$B = -4 \beta^2 L^4 t_0 (t_0 - K)$$

The total system cost $T_1$ resulting from the user equilibrium assignment can be calculated by adding the street flow cost to the total cost on the freeway as follows:

$$T_1 = K L (D - f_1) + 2 \beta L \int_0^{y_f} \left[ 2yK + Lc(f) \right] dy$$  \hspace{1cm} (2.6)

in which $D$ represents the total demand in the section of the corridor of length $L$, and depends on the overall width of the corridor.
• System Optimal Assignment

System optimal assignment occurs when the marginal costs on the freeway and on the city streets are equal. The latter is constant and equal to the average cost $K$, and the former can be obtained by differentiating the total freeway cost functions with respect to freeway flow. By equating these two marginal costs, we obtain the system optimal freeway flow, $f_2$, as follows:

$$f_2 = \mu \left[ -\mu K + (A + 3B)^{0.5} \right] / \left( 6 t_0 \beta L^2 \right)$$  \hspace{1cm} (2.7)

in which $A$ and $B$ are as defined above. The total cost $T_2$ for the system optimal assignment is obtained in a manner to equation (2.6). The difference, $\phi$ between the two cost functions can be used as an indication of the benefits from route guidance

$$\phi = T_1 - T_2$$

$$= \left( f_1 - f_2 \right) L + \mu^2 + K(f_1^2 - f_2^2) / 2 \beta L + (t_0 - K)(f_1 - f_2) L$$ \hspace{1cm} (2.8)

It should be noted that $\phi$ is considered as an upper limit to the potential benefits. They found that saving in total system travel time of the order of 3-4% can be achieved from route guidance and benefits are quite sensitive to city street speed.
2.4.3. Integrated Dynamic Assignment/Simulation Approach

Mathematical programming approaches for dynamic optimal routing has limitation on the implementation and computational work, and they are tested on very simple networks consisting of several links. Usually proof of convergence and the existence of the unique solution are the main focus of the approach. Thus it is considered that more appropriate model for evaluating dynamic route guidance benefits on a general networks are heuristic dynamic assignment model. Many of those approaches have been developed for the analysis of dynamic traffic flow and assignment in a realistic way. Especially, Assignment/Simulation models has been progressed with the development of computer simulation techniques and computational capabilities. The following approaches are recently developed integrated dynamic assignment/simulation methods.

Al-deek and Kanafani (1991) identified conditions under which route guidance information is useful and estimate its benefits in off-peak non-recurring congestion, using an deterministic queuing method and a simple road network with two parallel bottlenecks. With different cases of queue evolution mechanism by the availability of route guidance information, DRGS benefits to guided/unguided traffic and to the system are analyzed under user optimal strategy.

The study is focused on the DRGS benefits under non-recurring congestion, since DRGS is likely to be more beneficial. According to the recent researches, the benefits of route guidance under conditions of recurring congestion are marginal in the vicinity of 10 % savings of total travel time, since experienced travelers, who make up the major
portion of traffic in congested urban networks, have sufficient information to manage their route choice. However, under non-recurrent congestion, the lack of information about the severity and duration of an incident and its location vis-à-vis the rest of the network would leave the traveler insufficiently information to make appropriate route choice decision. According to the results of the study, as long as the fraction of vehicles equipped with DRGS is below a certain critical value, then all equipped travelers can be diverted and gain the maximum possible savings.

Furthermore, by extending DRGS information to potential travelers long before they approach incident location, they proposed to alter trip patterns including departure times, thereby spreading traffic over time in addition to space.

Ben-Akiva et al (1991) suggested that in case of the more advanced motorist information systems being developed now, two different types of approaches are being followed (in the US, Japan and Europe). In the first approach, drivers receive information from the system about traffic conditions which they use to figure the best routes. In the second approach, the system ascertains the vehicle's present location and desired destination and provides specific route directives to the driver. They classified traffic information available to drivers into three categories;

- Historical Information
  Information which describes the state of the transportation system during the previous time periods.

- Current Information
  The most up-to-date information about current traffic conditions.
• Predictive information

Information concerning expected traffic conditions during subsequent time periods when travel can occur.

Since driver's decisions are affected by expected network conditions, they suggested the most useful type of information to a driver faced with travel choice would be reliable predictive information. Unfortunately, the provision of such information is extremely difficult and beyond the scope of this research.

It is noted that existing driver information systems either simply pass to drivers information regarding current traffic and road conditions or provide drivers with route guidance information. However, in all these systems the impact of the guided information itself is not taken into consideration when providing drivers with route directives. In other words, the potential concentration of traffic on the recommended routes and the overreaction of drivers in their responses to guided information is ignored. The reliability of the guidance system is likely to be seriously questioned by users of the systems as the fraction of informed drivers increase.

They proposed that the ultimate development of driver information systems envisage a route guidance system with two way communication between the vehicles and a central traffic control system. Eventually the information in individual vehicles' route will be used to obtain reliable predictive information for route guidance and to set traffic control parameters to optimize overall network flows.
Halati and Boyce (1991) used computer simulation model, CORFLO, to access the effectiveness of four different types of navigation systems consisting of static map, dynamic map, route guidance, advanced route guidance systems as follows:

1. Static Map System - a descriptive open-loop system with simple directional aids and a map system

2. Dynamic Map System - a descriptive open loop system with simple directional aids, map system, and with added capability of identifying congested segments of a freeway

3. Route Guidance system - a prescriptive navigation system which identifies the "best" route to the driver; the system is a closed loop system providing two-way communication between the vehicle and control center to achieve user-optimal routing

4. Advanced Route Guidance System - a prescriptive, closed loop system similar to the route guidance system, with the additional capability of map display and display and directional aids.

The study is conducted for the Irvine network, Orange County, California. The result of the study shows that the performance of descriptive in-vehicle navigation system is depended on the initial network flow condition and could lead to severe worsening of traffic condition. The prescriptive systems including route guidance and advanced route guidance could substantially improve the traffic situation; the performance of these system is dependent on the level of drivers equipped with the navigation system. The appropriate level for the Irvine network is shown to be 30% or more.
Koutsopoulos and Yabronski (1991) examine the effects of design aspects of in-vehicle route guidance systems when used by a small number of participating vehicles. The design parameters of interest are the frequency of information updating, location of information, and level of intelligence. They performed a case study which indicated that there are significance trade-off among the design parameters and benefits to equipped vehicles due to the availability of information on traffic reductions were small with respect to average travel time reduction but significant with respect to average travel time improvement in travel time reliability.

In particular, they emphasized the effects of information on traffic delays due to incidents. A computer model which simulates vehicle trips through a network was used. They simulated a single vehicle traveling through the network among other flows; all the events which may occur are modeled probabilistically. At selected decision points in the network (information node), the simulated vehicle receives real-time information and the system calculate the "best" route using the shortest path algorithm. Especially queuing delays are estimated using deterministic queuing considerations. With the small suburban network (Sudbury, Massachusetts) on moderately congested network. They evaluated the performance of the system in terms of following measures; the mean travel time, the maximum travel time, and the standard deviation of travel time.

The average travel time is used to measure expected benefits from the user of DRGS in terms of travel time reduction, the standard deviation is a measure of the reliability of travel time and the maximum travel time is a measure of worst case consequence. The followings are summary of the simulation results;
1. Location of information nodes; when there is information at all nodes in the network, the reliability of travel time improves substantially up to 78%.

2. Frequency; Under the higher level of intelligence, are sensitive to the frequency of update since their values do increase as the update of information becomes less frequent. The 3 minute update is almost as good as the immediate information update, however as we move to longer time period between update, especially the lower level of intelligence, the system is not very effective.

3. System Intelligence; Comparison of the lower and higher level of intelligence results clearly show that the higher level of intelligence is better than the lower level remarkably.

Hounsell et al (1991) suggested the simulation technique as the tools for investigating and optimizing the DRGS control strategies, as well as system design. This method is particularly important as levels of congestion and proportions of guided vehicles increase, necessitate the use of time-varying multi-routing control strategies. They use CONTRAM traffic assignment model for this purpose.

It has the features of simulating unguided vehicle that incorporate the situation of drivers having a random imperfect knowledge of link journey times, which leads some incorrect route choice. This changes the routing solution from user equilibrium to stochastic user equilibrium. While unguided vehicle follows SUE routes, the guided vehicle follows actual optimum routes.
According to the results, the benefits of DRGS is maximum at the 10% penetration ratio of DRGS and it reduces as penetration ratio increase. Unguided vehicle also enjoy savings because guided vehicles are removed from routes congested by the non-optimum route choice of unguided drivers. They also conclude that DRG journey time savings increase with increasing incident severity and duration, until unguided drivers start to ‘self-divert’ and/or competing route become equally congested.

They also pointed out that Simulation modeling is an important tool in DRGS routing strategy assessment within a range of controlled network and traffic scenarios. However, it should be noted that the derivation of optimum strategies requires that the modeling accurately reflects traffic performance, DRGS operation, driver behavior and so on. Furthermore, they mentioned that the user-optimum routing will be required to maintain system credibility, but this should be considered towards a system optimum solution as the system grows.

Mahmassani and Peeta (1993) represented a comparative assessment of network cost and performance under time-dependent system optimal and user equilibrium assignment patterns using the simulation-based algorithm for the time-dependent assignment problem. They conducted experiment with a test network under progressively increasing network loading intensities. This research provides important implications for the DRGS strategies, since if the two extreme strategies are not perceptively different, coordinated cooperative SO route guidance imposed by a central controller may not be necessary, and less complicated and simpler to implement descriptive information to non-cooperating drivers may be sufficient. The system
performance is gauged using average network level traffic flow descriptor, in addition to the standard parameters like average travel time.

They use a heuristic iterative procedure in which DYNASMART developed by Mahmassani et al is used as a simulator to replicate the dynamics of traffic phenomena in response to a given assignment of vehicles to paths, and thereby evaluate the performance of the system. Figure 2.5 illustrates the framework of the system optimal assignment algorithm. The algorithmic step for UE assignment are virtually identical to those for the SO solution except for the specification of the appropriate link cost and the resulting path processing component of the methodology. That is, the solution to the time-dependent UE problem is obtained by assigning vehicle to the shortest average travel time paths instead of the least marginal cost paths in step 5.

The following is the summary of the simulation results

1. there is meaningful difference in overall system cost and performance between time-depend system optimal and user equilibrium assignments.

2. Thus there is considerable potential for system optimal, coordinated route guidance, especially in heavily congested (though not oversaturated) networks.

3. This results support that coordinated information is necessary beyond a certain market penetration.

4. SO is most effective when the traffic network is moderately to highly congested.

5. When the network is lightly or very highly congested (oversaturated), an SO assignment does not perform significantly better than UE.
They emphasized that simulation is an abstract representation of real-world traffic, and thus the research is exploratory rather than definitive in nature and the performance of dynamic traffic networks is critically sensitive to network topology and network loading pattern.

M. Cremer et al (1993) developed a method for determining optimal rerouting decision using traffic prediction model. Since the determination of optimal decisions for multi-destination, interacting rerouting under time-varying demand conditions is a rather complex problem, they proposed an iterative search procedure for its solution.

Moreover, they carried out comparisons between system and user optimum and it is shown that the user optimum, though generally preferable because of higher acceptance and there for better controllability, in special situation leads to impractical consequences. Such a critical case are the dissipation of congestion after clearing an accident, the imminent upstream extension of a congestion into an intersection and certain situations in cooperative rerouting scenarios.

Figure 2.6 illustrates the iterative optimal routing search procedure. As this scheme is still highly general and requires considerable computational effort which at this state impedes a real-time implementation, they applied it to typical examples and discuss implications with alternative choices of a system optimum or user optimum. They concluded that traffic prediction is indispensable in heavy demand scenario with disturbances which are real challenge for rerouting strategies.
Tokoro and Takaba (1994) proposed a travel time forecast algorithm which generates the forested travel time data that provide benefit under any condition (especially under high penetration condition). It is very important to find out the kinds of data which provide benefit under any condition and the method of making them. They proposed that efficient routing and benefits of DRGS depend on the kind of the link cost data, since algorithms for selecting optimal route uses the minimum total link costs of the networks. This means that if we make an error in selecting the data, DRGS will be useless, or harmful in the worse case.

They also understood that the causes of Braess Paradox comes from providing the same link cost data to all the guided vehicle periodically. In the low penetration condition there will be no problem because the guided vehicles are too few to make new congestion on a link. But in the high penetration condition, guided vehicle will concentrate at a link with a low cost and make congestion on it. Thus they suggested that the distortion factor to the link cost data and the variant cost data to each car might be used to solve the problem.

They also put the importance on the forecasted travel time data in that guided vehicles will have great influence on the future traffic condition under high DRGS penetration state. Thus DRGS needs a traffic condition forecasting algorithm which takes the route
Figure 2.5 Solution Algorithm for the System Optimal Dynamic Assignment.

(Mahmassani and Peeta, 1993)

Where

\(XP(O,D,T,K,I)\): The number of O-D desires in period \(T\) assigned to path \(K\) between Origin \(O\) and destination \(D\) at the \(I\)th iteration.

\(YP(O,D,T,K,I)\): All O-D desires in period \(T\) are assigned to auxiliary path \(K\) between origin \(O\) and destination \(D\) at the \(I\)th iteration

\[XP(O,D,T,K,I+1) = (1-\alpha) \times XP(O,D,T,K,I) + \alpha \times YP(O,D,T,K,I)\]

\(\alpha = 1/(I+1)\) \(\forall I = 0, 1, 2, \ldots\)
<Figure 2-6> Rough scheme of predictive control computation

(Cremer et. al., 1993)
decisions and future behavior of the guided cars into consideration. With such an algorithm, RGS predicts growing congestion before it gets fatal, and guided vehicles will be able to keep away from congestion when they plan their routes.

Using the above mentioned traffic data they developed a Dynamic Route Guidance Strategy as follows;

In-vehicle navigator selects the route of guided car by Dynamic Routing with forecasted link travel time data provided by traffic management center, and produce the Reservation Table. It contains Link ID and forecasted entering and leaving time of all links on the selected route. After selecting the route, in-vehicle navigator sends the Reservation Table to the roadside device.

Traffic management center has a Reservation number Table. This table contains numbers of cars which have reservations at each future time of each link. Roadside device sends Reservation Tables from in-vehicle navigators to the traffic management center renews the Reservation Number Table. and the traffic management center forecasts the future link travel time from Reservation Number Table and produce Forecasted Link Travel Time Table and broadcast it periodically.

The speed of the vehicles are decided by Greenberg Model. With the result of simulations, They have shown that the strategy is the best method in the high penetration condition.
2.5 Summary of Literature Review

Mathematical programming approaches for dynamic optimal routing has limitation on the implementation and computational work, and they are tested on very simple networks consisting of several links. Thus it is considered that more appropriate model for evaluating dynamic route guidance benefits on a general networks are heuristic dynamic assignment model. Many of those approaches have been developed for the analysis of dynamic traffic flow and assignment in a realistic way. Especially, Assignment-Simulation models has been progressed with the development of computer simulation techniques and computational capabilities.

Several researches are introduced for analyzing DRGS routing strategies using this methodology, but not much research has been done on the evaluation of adaptive routing strategy which consider both system optimal and user equilibrium strategy at the same time.
CHAPTER 3

COMPARISON OF DRGS ROUTING STRATEGIES

The chapter presents a comparative analysis for critical issues of dynamic route guidance system including system architecture and routing strategy. Firstly, infrastructure based DRGS and in-vehicle based DRGS are examined as alternative system architectures by comparing their advantages and disadvantages. The chapter also considers System Optimal (SO) and User Equilibrium (UE) traffic assignment model as alternative candidates for the routing strategy. The theoretical approach for investigating the differences between the two strategies is presented using mathematical programming method. Under various traffic situations, the benefits are measured by the total travel time reductions between the alternative routing strategies with idealized networks.

3.1 Comparison of the Alternative System Architecture

3.1.1 Advantages of Infrastructure Based System

♦ Low in-vehicle unit (IVU) cost for the drivers

The system has a major advantage of relatively inexpensive in-vehicle units (IVUs). With low cost investment of dynamic information transceiver, the car driver can be guided by the TMC’s optimal route planning. This could be helpful for the market penetration of DRGS.
Optimal route guidance and traffic control

The system can optimize the route guidance and traffic control simultaneously. This means that the planned destinations of travelers are used not only to determine their optimal routing, but the same information is used to estimate the traffic loads that are then used to set the parameters for traffic control devices such as signal, freeway ramps, and variable message signs. The function is essential to pursue the system optimal traffic operation.

Central system planning

Advanced modeling and simulation will be possible using databases within TMC. These models, working with historical data and real-time data, will allow the optimal use of the infrastructure-based system. For example, TMC can maintain an Origin/Destination database by writing on-ramp ID's into the tags as vehicles enter a freeway, and comparing these ID's to exit ramp ID's as they leave the freeway. This will result in the more accurate ability to plan and optimize the system as a result of having extensive, up-to-date historical Origin/Destination data. Without O-D information, advising diversion to another route or mode, when it is not known whether the diversion will reduce the individual drivers overall travel time, is not a good strategy.

Centralized traffic control

Centralized DRGS is attractive to traffic controllers who wish to keep the traffic pattern under their control, for example away from schools and quiet residential areas. The system also is expected to attract the drivers who are accustomed to the existing traffic facilities and condition to the newly developed alternative routes. In fact, without
centralized traffic control and real-time information, it is very difficult to cope with abnormal traffic conditions such as accidents, unexpected congestion and natural disaster.

3.1.2 Disadvantages of Infrastructure Based System

♦ **High infrastructure cost**

The centralized system are of very limited value without a significant investment of money and time in deploying the necessary supporting infrastructure.

♦ **Braess paradox**

Even though the driver has the option of choosing one of several criteria for route guidance (minimum time, most scenic, etc), the driver does not have as much control as decentralized route guidance system. This can results in Braess Paradox, which occurs when the guided vehicles are concentrated at a link with a low travel cost. If the routing computation is performed at the centralized infrastructure level, the user-modified routing schemes become more difficult to handle.

♦ **Privacy and inequity**

Since the driver needs to report his current position or destination to get the optimal routing information from TMC, the privacy might not be protected. Moreover, some driver group might be guided by the inferior route for the achievement of system optimal traffic operation especially in the severe incidents situation. Selection of the sacrificing driver group could cause the inequity problem.
3.1.3 Advantages of In-vehicle Based System

♦ Robustness

The architecture is robust because of two aspects; the centralized architecture is designed to have no single-point-failure. When an element fails, system performance may degrade, but the system does not fail; for example, the loss of TMC will result in the associated area processors taking over a limited decision making function from TMC. The other aspect of the robustness is the architecture’s ability to reconfigure the system in real time by “calling in” virtual beacons to provide coverage where fixed beacons or associated communications have failed.

♦ Low initial infrastructure cost and life cycle cost

Using the virtual beacons or RDS (Radio Data System), the system can be implemented initially without any infrastructure cost. The role of Traffic Information Center is to collect and distribute the dynamic information related with the current traffic condition. Since most of the equipment is out of the road, this architecture will also reduce the life cycle costs.

♦ User-specified criteria for route selection

Each driver can customize the link cost data at his own criteria in order to avoid Braess Paradox. The system is that individual route optimization can conceivably be based on multiple criteria specified by the driver. For example, driver who want to arrive quickly and avoid traffic signals can specify the relative weights of the these parameters and have the route optimized accordingly.
♦ **Anonymity**

Route guidance vehicle select their routes and guide themselves to their destination without reporting location or destination to the Transportation Management Center (TMC). By defining route selecting and guidance to be done on the vehicle, the concern of someone being able to track a user is eliminated. Considering the individual character of the typical American driver, the advantage of anonymity could gain the user acceptance in America.

♦ **Seamless nation-wide service availability**

Since the route guidance is done in the vehicle, the problem of availability of route selection services nation-wide or even jurisdiction-to-jurisdiction is avoided.

### 3.1.4 Disadvantages of in-vehicle based system

♦ **Lack of emergency control capability**

When emergency situation occurs, the system can't control the situation systematically. Travel times may actually increase, if too many vehicles are given the same alternate route. This situation could occur when route selection is performed in a large percentage of vehicles, but the route selection process in each vehicle does not consider estimates of the reactions of other vehicles to the same routing information.

♦ **Market penetration**

Market penetration is the problem. It will take long time to equip the DRGS because the
cost of in-vehicle units in the decentralized route guidance system will be 3 to 6 times higher than that of centralized route guidance system.

♦ System vs. user optimal

Under abnormal traffic condition such as congestion or accidents, the DRGS user will choose their self-interest optimal routing, which may become very far off from the system optimum, further aggravating the abnormal traffic congestion. It has been suggested that the advent of route guidance system has made the difference between user optimal, favored by the individual drivers, and system optimal, favored by traffic authorities.

♦ Braess paradox

As the market penetration of DRGS grows, there will be Braess Paradox which comes from providing the same data to all the cars. Accordingly DRGS needs a traffic condition forecasting algorithm in the future which takes the route decisions and future behavior of the guided vehicles into consideration.

3.1.5 Relationship between System Architecture and Routing Strategy

Table 3.1 is a summary table of the characteristics of the two system architecture mentioned above. Each system architecture is establishing the strategies in order to complement their disadvantages such as privacy and initial cost.

From the viewpoint of DRGS routing strategy, Infrastructure based system has advantage of pursuing system optimal traffic operation, which is more essential under
abnormal traffic conditions such as non-recurrent congestion and natural disaster. But it should concern the problem of user compliance, when some of equipped drivers are urged not to choose minimum travel time path for the whole system optimal.

On the other hand, In-vehicle based system can utilize the user-specified route selection criteria to avoid "Braess Paradox" under normal traffic condition. However, it may be of no use under abnormal traffic conditions and high DRGS market penetration state. Conclusively, it is envisaged that Infrastructure based system is more appropriate system architecture for the DRGS routing strategy under non-recurrent congestion.
Table 3-1 Comparison of the alternative DRGS system architecture

<table>
<thead>
<tr>
<th></th>
<th>Infrastructure based Architecture</th>
<th>In-vehicle based Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driver</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Cost</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Market Penetration</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Equity</td>
<td>poor</td>
<td>good</td>
</tr>
<tr>
<td>Privacy</td>
<td>poor</td>
<td>good</td>
</tr>
<tr>
<td>Compliance</td>
<td>poor</td>
<td>good</td>
</tr>
<tr>
<td><strong>Traffic Authority</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Cost</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Control</td>
<td>good</td>
<td>poor</td>
</tr>
<tr>
<td><strong>System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robustness</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Communication</td>
<td>very high</td>
<td>high</td>
</tr>
<tr>
<td>Braess paradox</td>
<td>poor</td>
<td>poor</td>
</tr>
<tr>
<td><strong>Routing Strategy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal condition</td>
<td>System, User Optimal, Controllable</td>
<td>User Optimal, Uncontrollable</td>
</tr>
<tr>
<td>Abnormal condition</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2 Routing Strategies for DRGS

As discussed in Chapter 2, there are two well-known principles for traffic assignment which were first introduced by Wardrop (1952).

(i) "The journey time on all routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route."

(ii) "The average journey time is a minimum."

The first principle ensures that no traveler can improve his travel time by unilaterally changing routes. In other words, it can be described as a stable condition which is achieved when there is no force to move the flows out of the equilibrium situation. Thus, the flows resulting from the assignment based upon the first principle is called "User Equilibrium".

On the other hand, "System Optimal" is the traffic assignment based upon second criterion to minimize the total travel time spent in the whole network. Generally this flow pattern does not represent an equilibrium condition, since drivers can reduce their travel time by unilaterally changing routes. Hence, this traffic assignment technique has not been adopted practically as a model of actual driver behavior and equilibrium.

With the advent of Dynamic Route Guidance System, Wardrop's assumptions that driver will have perfect knowledge of link travel times when selecting their routes, is likely to become realistic. This makes the Dynamic Route Guidance System feasible to achieve
the most efficient routing strategy which minimize the total system travel time especially under recurrent and non-recurrent congestion. Thus, the evaluation of the potential benefits of the alternative strategies under various traffic situations will play an important role in the successful development of effective DRGS.

3.2.1 User Equilibrium Strategy

The User Equilibrium (UE) route guidance strategy can be achieved by performing UE traffic assignment, which was firstly developed as a mathematical optimization problem by Beckmann et al. (1956) as follows;

Consider a transportation network represented by a directed graph $G=(N,K)$, where $N$ is the set of nodes and $K$ is the set of links. A node represents an origin, a destination or an intersection of streets. The User Equilibrium assignment is formulated as following:

$$\text{Minimize } Z_i(x) = \sum_k \int_0^{x_k} C_k(w)dw$$

subject to:

1. flow conservation constraints:

If there are $Q_{od}$ trips that need to travel from origin "o" to destination "d" then the summation of flows on all paths $(p)$ form "o" to "d" must equal to $Q_{od}$. This is expressed as:

$$\sum_p f_{p}^{od} = Q_{od} \quad \forall o,d$$

2. Non-negativity constraints:
\[ f_p^{od} \geq 0 \quad \forall p, o, d \]

3. Definitional constraints for incidence relationships in the network structure.

\[ x_k = \sum_o \sum_d \sum_p f_p^{od} \delta_{k,p} \quad \forall k \]

where,

- \( C_k(w) \) is the travel time experienced by each driver on link \( k \) as a function of flow \( w \) on link \( k \).
- \( f_p^{od} \) is the flow on path \( p \) connecting O-D pair \( o-d \)
- \( Q_{od} \) trip rate between origin \( o \) and destination \( d \)
- \( x_k \) traffic flow on link \( k \)
- \( \delta_{k,p} \) indicator variable: 1 \( \rightarrow \) if link \( k \) is on path \( p \) between O-D pair \( o-d \)
  
  \[ 0 \rightarrow \text{otherwise} \]

3.2.2 System Optimal Strategy

The System Optimal (SO) route guidance strategy also can be achieved by implementing SO traffic assignment. Intuitively, the objective function of system optimal traffic assignment can be formulated by the following mathematical program:

\[
\text{Minimize} \quad Z_2(x) = \sum_k x_k C_k(x_k)
\]

subject to the same constraints as the User Equilibrium assignment i.e.

\[ \sum_p f_p^{od} = Q_{od} \quad \forall o, d \]

\[ f_p^{od} \geq 0 \quad \forall p, o, d \]
\[ x_k = \sum_o \sum_d \sum_p f^{od}_{p} \delta_{k,p} \quad \forall k \]

### 3.2.3 Derivation of Link Performance Function

It should be noted that this optimization problem has a unique solution if following two assumptions are satisfied. [See Sheffi(1985)] First, link performance function, \( C_K(w) \), is positive and monotonically increasing, which means that the function is strictly convex. Second, the travel time on a given link \( a \) is independent of the flow on any other link in the network. These assumption can be written mathematically as

\[
\frac{\partial C_k(x_k)}{\partial x_k} > 0 \quad \forall k
\]

\[
\frac{\partial C_k(x_k)}{\partial x_l} = 0 \quad \forall k \neq l
\]

In order to satisfy the first condition for uniqueness of the solution, the link performance function here is assumed as a polynomial type. It is derived from BPR function as follows,

\[
t_t(v_i) = tf_i(1 + a_i \left(\frac{v_i}{c_i}\right)^b)
\]

(3.1)

where,

\( v_i \): prevailing volume on link \( i \)

\( tf_i \): free flow travel time

\( c_i \): Capacity of the link \( i \)

\( a \): parameter

\( b \): power
Substitute the parameters of Eq. (3.1) as follows,

$$
\alpha_i = tf_i
$$

$$
\beta_i = a \times \frac{tf_i}{c_i^b}
$$

$$
\gamma = b
$$

then, we get

$$
it_i(v_i) = \alpha_i + \beta_i(v_i)^\gamma
$$

(3.2)

A consistent link performance function is also adopted in INTEGRATION traffic simulation model. It will be used later as a simulation model for evaluating DRGS routing strategies. The link performance function of INTEGRATION (Van Aerde 1994) is

$$
t = t_f \left\{ 1 + \left( \frac{S_f}{S_c} - 1 \right) \left( \frac{V}{C} \right)^3 \right\}
$$

Where: $t = \text{link travel time (seconds)}$

$t_f = \text{travel time when traveling at the free speed (seconds)}$

$S_c = \text{speed at capacity (km/h)}$

$S_f = \text{free speed (km/h)}$

$C = \text{link capacity (vph)}$

$V = \text{link flow (vph)}$

If we follow the parabolic speed-flow relationship proposed by Greenshields, the speed at capacity $S_c$ is set to half of the free speed $S_f$ [See Highway Capacity Manual (1985)]. Accordingly, the link performance function is simplified as follows;

$$
t = t_f \left( 1 + \left( \frac{V}{C} \right)^3 \right)
$$

$$
= t_f + \frac{t_f}{C^3} (V)^3
$$

(3.3)
Using this link performance function, the objective function for simple networks using User Equilibrium route guidance strategy is reformulated as follows:

$$\min Z_1(x) = \sum_k \int_0^{x_k} \left( t_f + \left( \frac{t_f}{C_k} \right)x^3 \right) dx$$  \hspace{1cm} (3.4)$$

The objective function for simple networks using System Optimal route guidance strategy can also be reformulated as follows:

$$\min Z_2(x) = \sum_k x_k \left[ t_f + \left( \frac{t_f}{C_f} \right)x_k^2 \right]$$  \hspace{1cm} (3.5)$$

As the formulation is a convex nonlinear problem, Sheffi's algorithms can be used to solve it. [See Sheffi(1985)]

3.3 Comparison of User Equilibrium vs. System Optimal

3.3.1. The Differences between UE and SO

It can be seen that UE route guidance strategy considers average travel time when selecting the minimal path, while SO route guidance strategy considers marginal travel time on each link. If the traffic flow over the network is relatively low, the difference between the UE and SO flow is negligible. This is because the marginal travel time on each link at this non-congested range is very small. As the link flow increases, the marginal travel time will also increase proportionally. This will result in a different UE and SO flow pattern.
To illustrate this better, a simple network with two alternative links is used. It is shown in Figure 3.1.

![Freeway diagram](image)

**Freeway**

**Arterial**

*Figure 3.1 A simple network of two alternative links*

The objective function (3.5) can be directly used for solving the User Equilibrium flow pattern. However, this is not an optimal solution from the viewpoint of the whole system. That is, if one driver changes his route from link 2 to link 1 then the travel time for each of the remaining drivers is reduced by \( \frac{dtt_i(v_i)}{dv_i} \), even though the travel time of the driver in alternate route will be increased by the amount of \( |t_1(0) - t_2(q)| \). The total travel time reduction by changing route from link 1 to link 2 is achieved until the point when

\[
itt_i(v_i) + v_i \frac{dtt_i(v_i)}{dv_i} = itt_2(v_2) + v_2 \frac{dtt_2(v_2)}{dv_2}
\]

In other words, to solve the System Optimal flow pattern, the travel time function should be modified to consider the marginal contribution of an additional driver on link \( i \) to the total travel time as follows:

\[
itt_i(v_i) \triangleq itt_i(v_i) + v_i \frac{dtt_i(v_i)}{dv_i}
\]
Figure 3.2 demonstrates the hypothetical cost and marginal curves for the simple network as a function of flow on arterial with a fixed total demand from O to D. Graphically, it shows the User Equilibrium (UE) at the intersection of alternative cost curves (ALC and FLC) and the System Optimum (SO) at the intersection of alternative marginal cost curves (ALMC and FLMC).

### 3.3.2. Example Problem

Consider an idealized simple network as shown Figure 3.1. The freeway and the arterial have two lanes. The network has the following link characteristics,

- freeway capacity $C_f = 2000$ vehicle per hour (vph)/lane
- arterial capacity $C_a = 1000$ vehicle per hour (vph)/lane
- freeway and arterial distance $l_f = l_a = 2$ mile
- free flow speed on freeway $s_f = 65$ mile per hour (mph)
- free flow speed on arterial $s_a = 45$ mile per hour (mph)
- total traffic demand varies 0 vph to 6000 vph (system capacity)

Using this information, the parameters of the link performance function of the objective function (3.2) are obtained as follows;
Figure 3.2 Illustration of difference of user equilibrium vs. system optimal flow pattern
\[ \alpha_f = \frac{t_f}{s_f} = \frac{2 \times 60}{65} = 1.85 \text{ min} \]

\[ \alpha_a = \frac{t_a}{s_a} = \frac{2 \times 60}{45} = 2.67 \text{ min} \]

\[ \beta_f = \frac{t_f}{C_f^3} = \frac{l_f}{s_f \cdot C_f^3} = \frac{2 \times 60}{65 \times \left(\frac{2000 \times 2}{60}\right)^3} = 6.244 \times 10^{-6} \]

\[ \beta_a = \frac{t_a}{C_a^3} = \frac{l_a}{s_a \cdot C_a^3} = \frac{2 \times 60}{45 \times \left(\frac{1000 \times 2}{60}\right)^3} = 7.2 \times 10^{-5} \]

Hence, the formulation of mathematical programming for User Equilibrium route guidance strategies is expressed as,

\[
\min \quad Z_i(x) = \int_0^{x_f} (\alpha_f + \beta_f x^3) \, dx + \int_0^{x_a} (\alpha_a + \beta_a x^3) \, dx
\]

subject to

\[
\begin{align*}
x_f + x_a &= Q \\
x_f, x_a &\geq 0
\end{align*}
\] (3.6)

Similarly, the formulation of mathematical programming for System Optimal route guidance strategies is expressed as,

\[
\min \quad Z_i(x) = x_f (\alpha_f + \beta_f x_f^3) + x_a (\alpha_a + \beta_a x_a^3)
\]

subject to

\[
\begin{align*}
x_f + x_a &= Q \\
x_f, x_a &\geq 0
\end{align*}
\] (3.7)

A computer program has been developed using MATLAB to obtain the eq(3.6) and eq. (3.7) nonlinear Programming solutions. (See Appendix I) Table 3.2 and Table 3.3 shows the optimal split of the traffic volume for each route guidance strategy with the increase of traffic demand level till it reaches the system capacity Q.
Figure 3.3 and Figure 3.4 illustrate the distribution of assigned traffic volumes on alternative routes graphically. The graphics imply that SO route guidance strategy utilizes the network fully since it starts to assign the traffic volume to the arterial when the level of traffic demand approaches 30% of the system capacity.

On the other hand, UE route guidance strategy does not use the arterial until the level of traffic demand reaches half of the system capacity. It has also observed that the route traffic volumes of SO route guidance strategy are more evenly distributed than that of UE route guidance strategy. These results are consistent with the fact that the SO route guidance strategy pursues the maximum utilization of the system.

The differences in total travel time between the UE and SO strategies are illustrated in Figure 3.5. As we expected, there is no remarkable difference between both low and high traffic demand. This implies that the gap of marginal travel time between the alternatives is negligible in low or high traffic demand range. However, significant differences are found within the mid-range traffic demand. In this case, the maximum total travel time difference occurs when the level of traffic demand is half of the system capacity. At this point, SO route guidance strategy can save more than 11% of the total travel time of UE route guidance strategy. It is also noted that UE traffic assignment shows relatively unbalanced distribution around the mid-range traffic demand especially when the maximum difference in total travel time occurs.
Table 3.2 User equilibrium traffic assignment

(unit; veh/min)

<table>
<thead>
<tr>
<th>Total Demand</th>
<th>.1Q</th>
<th>.2Q</th>
<th>.3Q</th>
<th>.4Q</th>
<th>.5Q</th>
<th>.6Q</th>
<th>.7Q</th>
<th>.8Q</th>
<th>.9Q</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeway</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>51.62</td>
<td>55.20</td>
<td>60.29</td>
<td>66.08</td>
<td>66.67</td>
</tr>
<tr>
<td>Arterial</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.38</td>
<td>14.80</td>
<td>19.71</td>
<td>23.92</td>
<td>33.33</td>
</tr>
<tr>
<td>Total travel</td>
<td>18.56</td>
<td>38.0</td>
<td>60.56</td>
<td>89.98</td>
<td>131.53</td>
<td>162.54</td>
<td>203.01</td>
<td>257.46</td>
<td>328.67</td>
<td>431.25</td>
</tr>
<tr>
<td>Time (min)</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Table 3.3 System optimal traffic assignment

(unit; veh/min)

<table>
<thead>
<tr>
<th>Total Demand</th>
<th>.1Q</th>
<th>.2Q</th>
<th>.3Q</th>
<th>.4Q</th>
<th>.5Q</th>
<th>.6Q</th>
<th>.7Q</th>
<th>.8Q</th>
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</tr>
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<td>Arterial</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>12.24</td>
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<td>20.00</td>
<td>23.43</td>
<td>26.74</td>
<td>33.33</td>
</tr>
<tr>
<td>Total Travel</td>
<td>18.56</td>
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<td>60.56</td>
<td>87.29</td>
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<td>152.17</td>
<td>196.38</td>
<td>252.78</td>
<td>325.14</td>
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</tr>
<tr>
<td>Time (min)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Figure 3.3 Distribution of System optimal routing
Figure 3.4 Distribution of User equilibrium routing
Figure 3.5 Differences between UE and SO routing
3.3.3 Sensitivity Analysis

The sensitivity analysis of the differences between UE and SO route guidance strategies are performed by changing the parameters of the link performance function in the alternate route. The factors which affect the link performance function include total traffic demand and link characteristics such as distance, free flow speed and capacity.

The difference in the total travel time between UE and SO route guidance strategy is demonstrated by 3-dimensional graphics using MATLAB programming. [See Appendix II] Figure 3.6 depicts the 3-dimensional distribution of the differences in total travel time between the two strategies as total traffic demand and distance of arterial varies simultaneously. The graphic shows that there are no differences between the two strategies under the low total traffic demand below 30 vehicle per minute which is 30% of system capacity. This is because the freeway only is used for both UE and SO route guidance strategies. However, as the total traffic demand increases, the difference increases drastically and gradually decrease after it reaches its maximum point. It should be noted that the maximum point shift upward and maximum value increase as the distance of alternate route increases.

Figure 3.7 also depicts the 3-dimensional distribution of the differences in total travel time between the two strategies as total traffic demand and free flow speed of alternate route vary simultaneously. The graphic shows that the differences start to increase after the level of total traffic demand is over 40 vehicles per minute and also gradually decrease after it reaches its maximum point. It should be noted that the maximum point
shift downward and maximum value decrease as the free flow speed of alternate route increase.

The 3-dimensional distribution of the difference between UE and SO route guidance strategies when the capacity of alternate route changes with total traffic demand is illustrated in Figure 3.8. The graphic depicts that there is also no difference under the low total traffic demand of below 30 vehicle per minute. In this case, it is noted that the maximum points concentrate in the vicinity of 50 vehicle per minute which is 50% of system capacity regardless of the capacity variation of alternate route. The magnitudes of the differences are relatively small and they do not vary much with the variation of alternate route's capacity.
Figure 3.6 Difference between UE and SO by alternate route’s distance
Figure 3.7 Difference between UE and SO by alternate route's free flow speed
Figure 3.8 Difference between UE and SO by alternate route's capacity
3.4 Comparison of UE vs. SO under Incident Condition

It is generally believed that DRGS will be more beneficial when the non-recurrent congestion caused by accidents or roadwork occurs. It is reasonable to believe that under normal traffic conditions, only a few drivers need to re-route themselves to keep the equilibrium state in the network; but under abnormal traffic conditions like non-recurrent traffic congestion, most of the driver will need the DRGS re-routing information to settle the disequilibrium status.

Therefore, it is a critical task to develop a DRGS routing strategy which maximizes the DRGS benefits under non-recurrent congestion. In this context, the research will focus on the quantitative evaluation of DRGS routing strategies under non-recurrent congestion.

3.4.1 The Difference Between UE and SO under Incident Condition

Consider the following simple network with a incident on freeway.

![Diagram of a simple network with an incident on the freeway](image)

Figure 3.9 A simple network with incident on freeway
Without question, delays on the freeway with incident will increase more rapidly than on the freeway without incident because of the freeway capacity reduction due to the lane or shoulder blockage. The increased delays will result in more steep slopes both on link cost function (FLC') and link marginal cost function (FLMC') as shown in Figure 3-10. This demonstrates the hypothetical cost and marginal curves for the simple network with incident condition. It should be noted that the arterial traffic volumes of the new User Equilibrium (UE') and System Optimal (SO') status are increased by the incident effects, as compared to that of User Equilibrium (UE) and System Optimal (SO) status without incident.

3.4.2 The Sensitivity Analysis by Freeway Capacity Reduction

The sensitivity analysis of the differences between UE and SO route guidance strategies under incident situation are performed by changing the freeway capacity from 0 to 4000 vehicle per hour. Figure 3.11 depicts the 3-dimensional distribution of the differences in total travel time between the two strategies as total traffic demand and freeway capacity vary simultaneously. The graphic shows that there is no big difference between the two strategies if the level of capacity reduction lies between 50% and 100%. This is because there is not enough capacity to be utilized for system optimal route guidance in the system.

However, if the incident severity is low, the difference is relatively high, especially in the traffic demand. However, as the incident severity is alleviated, the differences increase and gradually decrease after it reaches its maximum point, which is in the mid-range of
3000 vph to 4000 vph of traffic demand. It should also be noted that the maximum point shift upward and maximum value increases as the capacity reduction decreases.

3.4.3 The Existence of “Braess’ Paradox” under Incident Condition

It is a well-known fact that a failure to realize the fundamental difference between the SO and UE flow pattern can lead to pseudo paradoxical scenarios. The most famous of these is known as ‘Braess Paradox’. The paradox occurs when the individual choice of route is performed without the consideration of the effect of the action on other network. We expect a total travel time reduction which is a system optimal perspective by adding a link while the drivers choose their route by UE criteria. Thus the resulting UE flow pattern does not necessarily reduce the total travel time.

It should be noted that the paradox does not always occur only with the addition of new link. It can also happen when the database of available links in the Route Guidance System network is expanded to the local roads. Furthermore, it can happen when we consider diversion routes under incident situation. (Van Aerde 1991)

Figure 3.12 shows the change of the difference between UE and SO strategies with multiple alternate routes by incident, that is capacity reduction in freeway. It is noted that the distributions of the differences of the two traffic conditions don't have the similar shapes. This implies that careful consideration should be given for determining route guidance strategies.

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Figure 3.10 Difference between UE and SO under incident condition
Figure 3.11 Difference Between UE and SO by freeway reduced capacity
For example, there are no significant differences between the two strategies under normal condition, when the level of traffic demand lies between 60% and 80% of the system capacity. But once an incident occurs, the difference reaches its maximum within the same level of traffic demand. In other words, when the incident occurs with the steady-state traffic demand, we can save considerable total travel time by changing the routing strategies from UE to SO. This will be the basis in the following proposed methodology for determining optimal route guidance strategies under non-recurrent congestion.
Figure 3.12 Differences between UE and SO with multiple alternate routes
There have been numerous efforts during the last decade to evaluate the benefits of DRGS. These results suggest that the benefits of DRGS are marginal under conditions of recurring congestion. Experienced travelers, who make up the major portion of the traffic in congested networks, have sufficient information to choose their route under recurrent congestion.

It is thus expected that DRGS is likely to be more useful under conditions of non-recurrent congestion, as may be caused by incidents. Under these conditions, the lack of information about the severity and duration of an incident and its location would leave the travelers insufficiently informed to make appropriate route choice decision.

Furthermore, by extending DRGS information to potential travelers long before they approach incident locations, it may be possible to further reduce potential congestion by altering trip patterns including departure time in addition to space. Thus, providing reliable information about the incident and optimal route recommendation are essential to DRGS.

As discussed in Chapter 3, the travel time reduction by system optimal strategy over user equilibrium strategy varies with the traffic condition and network configuration. Therefore, an adaptive strategy which considers the variation of travel time saving is needed to provide efficient route guidance especially under non-recurrent congestion. Here, a discrete deterministic queueing model is developed to estimate delay dynamically caused by freeway
incidents. Based on this, an adaptive dynamic route guidance methodology for incident management is proposed.

4.1 Dynamic Estimation of Incident Delay

Any freeway incident can cause delay either directly via lane closures or indirectly via "gawker block". The extent of incident impacts depend on the level of traffic demand during the incident, the duration of the incident, and the degree of capacity reduction. Here a discrete dynamic model for estimating incident delay has been suggested using deterministic queueing model.

4.1.1. Deterministic Queueing Model

Deterministic queueing model which assumes uniform flow rate can give the information about the exact queue length and delayed time within a given time period. Figure 4.1 shows the process of incident occurrence and response with the time-varying length of the queue and delay due to incident.

The area, $D_1$, is the total delay with diversion due to the incident which depends on the incident duration (ID) and the reduced capacity (rQ) by the incident type and its severity. It also shows that reduction in incident duration reduces the total delay. Moreover, route guidance information about incident duration can allow individuals to divert to alternate routes before joining the queue. This would reduce the arrival rate and the incident bottleneck, which will save additional total delay caused by no diversion.
Figure 4.1 Deterministic queueing diagram by incident condition
(Source: Cambridge Systematics, Inc. 1990)
With the information about the duration and reduced capacity by the incident, we can get various incident data including the time to normal flow ($t_3$), maximum queue length (MQL) and maximum waiting time (MWT) and so on. [See May 1990]

### 4.1.2 Dynamic Delay Estimation

A discrete model for estimating dynamic incident delay is developed based on deterministic queueing model. The model will be a component of link performance function for the optimization problem. Figure 4.2 illustrates the dynamic variation of incident queueing delay with discrete time slice ($\Delta t$). Average queueing delay of each time slice can be calculated using geometry of the diagram as follows:

First, the queue delay at time $n$ ($W_n$) is obtained by

\[
W_1 = \left( \frac{q_1}{rQ} - 1 \right) \Delta t
\]

\[
W_2 = W_1 + \left( \frac{q_2}{rQ} - 1 \right) \Delta t
\]

\[
W_3 = W_2 + \left( \frac{q_3}{rQ} - 1 \right) \Delta t
\]

\[\vdots\]

\[
W_n = W_{n-1} + \left( \frac{q_n}{rQ} - 1 \right) \Delta t
\]  

(4.1)

where,

$W_n$: the queue delay for the lastly arrived vehicle at time interval $n$

$q_n$: traffic demand at time interval $n$

$rQ$: reduced capacity
The area $d(n)$, which implies the total queueing delay for $q_n$, is calculated by as follows:

$$d_1 = \frac{W_1}{2} q_1 \Delta t$$

$$d_2 = \frac{W_1 + W_2}{2} q_2 \Delta t$$

$$d_3 = \frac{W_2 + W_3}{2} q_3 \Delta t$$

$$\vdots$$

$$d_n = \frac{W_{n-1} + W_n}{2} q_n \Delta t$$

The average queueing delay at time slice $n$ is calculated as

$$a_1 = \frac{W_1}{2} q_1 \Delta t \cdot \frac{1}{q_1 \Delta t} = \frac{W_1}{2}$$

$$a_2 = \frac{W_1 + W_2}{2} q_2 \Delta t \cdot \frac{1}{q_2 \Delta t} = \frac{W_1 + W_2}{2}$$

$$a_3 = \frac{W_2 + W_3}{2} q_3 \Delta t \cdot \frac{1}{q_3 \Delta t} = \frac{W_2 + W_3}{2}$$

$$\vdots$$

$$a_n = \frac{W_{n-1} + W_n}{2} q_n \Delta t \cdot \frac{1}{q_n \Delta t} = \frac{W_{n-1} + W_n}{2}$$

Thus, we can derive a equation of average incident delay as a function of traffic flow $q_t$ at time $t$ as follows:

$$a(t) = \frac{W(t-1) + W(t)}{2}$$

Using Eq(4.1),

$$a(t) = \frac{W(t-1)}{2} + \frac{W(t-1) + (\frac{q_n - rQ}{2rQ})}{2}$$

$$= W(t-1) + \frac{(q_n - rQ) \Delta t}{2rQ}$$

$$= W(t-1) - \frac{1}{2} \Delta t + \frac{\Delta t}{2rQ} q(t)$$
Figure 4.2 Discrete deterministic queueing model for estimating incident delay
This function is used to incorporate queueing delay under incident condition in the link performance function as follows:

\[
C(x(t)) = \alpha + \beta x(t) \quad \text{if } a(t) = 0
\]

or

\[
C(x(t)) = \alpha + \beta x(t)^3 + a + bx \quad \text{if } a(t) > 0
\]

where,

\[
a = W_{n-1} - \frac{1}{2} \Delta t
\]

\[
b = \frac{\Delta t}{2rQ}
\]

Figure 4.3 illustrate the flow chart for dynamic delay estimation using deterministic queueing model. There are two equations for each incident situation as follows:

\[
W_n = W_{n-1} + \left(\frac{q_n}{rQ} - 1\right)\Delta t \quad \text{for } t_n^d < \text{ID} \quad (4.2)
\]

\[
W_n = W_{n-1} + \left(\frac{q_n}{Q} - 1\right)\Delta t \quad \text{for } t_n^d \geq \text{ID} \quad (4.3)
\]

where,

\[
t_n^d : \text{the departure time for last vehicle arriving at time interval } n
\]

\[
\text{ID} : \text{incident duration (minutes)}
\]

In the following section, an adaptive strategy for DRGS which has a step-wise feedback control loop is proposed to implement efficient real-time optimal route guidance strategy under non-recurrent congestion. The methodology utilizes the results of comparison of UE and SO strategies and dynamic queueing delay estimation model.
Figure 4.3 Algorithm for estimating incident delay
4.2 An Adaptive Methodology for DRGS under Non-Reccurrent Congestion

From the viewpoint of DRGS routing strategy, system optimal strategy has an advantage of saving a certain amount of total system travel time. It is likely to be more beneficial under abnormal traffic conditions such as non-recurrent congestion and natural disasters. But an issue of great concern is the problem of user compliance when some of the equipped drivers are urged not to choose minimum travel time path for the whole system optimal. This is because the system optimal route may not be the best route for each individual drivers.

Experienced drivers might use their own perceived travel time based on experience for selecting their routes. They do this when they believe that the perceived difference in travel time between the recommended route and their own improvised routes exceed a certain marginal level. Therefore, it should be considered that a certain ratio of equipped drivers will not follow the system-optimal route guidance information. Undoubtedly, this ratio can be applied to the User Equilibrium strategy, but it is relatively small.

In addition to this, it is suggested that careful consideration should be given by adopting minimum travel time saving ratio, when SO strategy is implemented. The purpose of adopting minimum travel time saving ratio is to prevent improper use of system optimal strategy. It is believed that at least a certain percentage should be saved by implementing SO strategy, since SO strategy might lose its credit gradually by sacrificing the travel time of some of equipped drivers. Here 5% of minimum travel time saving ratio has been assumed.

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4.2.1 Proposed Methodology

As discussed in Chapter 3, it is proposed that an adaptive routing strategy is required for efficient control of dyadic route guidance system especially under non-recurrent congestion. Figure 4.4 demonstrates the step-wise feedback methodology of adaptive routing strategy for DRGS. The detailed procedure is as follows;

1) Determine the exogenous variable

It is important to set up exogenous variables such as the user compliance ratio, minimum travel time saving ratio and the market penetration ratio. These values can be obtained by field surveys and interviews or lab experiments, which are out of scope in this research. Instead, sensitivity analysis will be performed for these variables in the next chapter using a simulation model.

2) Monitor real-time traffic situation

Using advanced traffic technology, a series of real-time traffic data which describe the current traffic situation are available for the traffic networks. Especially, real-time information about current traffic flow pattern and queue length during the incident process will play key roles in the proposed methodology.

3) Starting incident situation

Once an incident is detected, it will automatically trigger the dynamic incident delay estimation module using current traffic flow and basic incident information including the location of the incident, the number of blocked lanes, and incident type (e.g., accident or disablement)
The information will be used for defining the incident duration and reduced capacity. Lindley suggested a table of average incident duration for freeway section based upon previous work done by Owen and Urbanek, 1978. [see Table 4.1] He also provided the information about the fraction of freeway section capacity available under incident conditions. [see Table 4.2]. Using this table, the reduced capacity due to the incident can be computed.

4) Solve UE and SO route guidance strategies
As discussed in previous chapter, the UE and SO route guidance strategies will be obtained by using nonlinear programming method with the revised link performance function as proposed in section 3.1. User compliance ratio for system optimal strategy is applied before the two strategies are compared.

5) Comparison & selection
The difference in total travel time between UE and SO strategies will be the criteria for determining optimal strategy for current traffic situation. Minimum travel time saving ratio should be applied to system optimal strategy for the comparison. As noted in previous chapter, the difference varies due to the current traffic flow pattern, the severity of incident, the number of available alternate routes and its link characteristics.

6) Implementation
The selected route guidance strategy will be implemented promptly to the networks. The results of the implementation will be captured by the traffic monitoring system after one time slice passed. This adaptive routing strategy for DRGS will continue until the time to normal flow.
Table 4.1 Average incident duration times for freeways (Lindley 1987)

<table>
<thead>
<tr>
<th>Existence of shoulder</th>
<th>Accident type</th>
<th>Location of the incident</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Shoulder</td>
</tr>
<tr>
<td></td>
<td></td>
<td>three</td>
</tr>
<tr>
<td>Shoulder</td>
<td>Disablement</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Accident</td>
<td>40</td>
</tr>
<tr>
<td>No shoulder</td>
<td>Disablement</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Accident</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 4.2 Fraction of freeway section capacity available under incident condition (Lindley 1987)

<table>
<thead>
<tr>
<th>No. of freeway lanes in each direction</th>
<th>Shoulder</th>
<th>Lane blocked</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Disablement</td>
<td>Accident</td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
<td>0.81</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>0.83</td>
</tr>
<tr>
<td>4</td>
<td>0.99</td>
<td>0.85</td>
</tr>
<tr>
<td>5</td>
<td>0.99</td>
<td>0.87</td>
</tr>
<tr>
<td>6</td>
<td>0.99</td>
<td>0.89</td>
</tr>
<tr>
<td>7</td>
<td>0.99</td>
<td>0.91</td>
</tr>
<tr>
<td>8</td>
<td>0.99</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Figure 4.4 The Step-wise feedback methodology for DRGS under non-recurrent congestion
4.3 Computation Results

Several computer programs developed using MATLAB are executed to demonstrate the adaptive routing procedure of DRGS with the assumption of 5% minimum travel time saving ratio, 100% user compliance ratio and market penetration ratio. Network scenarios are designed to compare the performance of the strategy. The scenarios are divided into three categories by incident duration, freeway traffic demand and arterial traffic demand.

Figure 4.5 to Figure 4.10 illustrate the change of total travel time reduction ratio as the incident progress and retrogress. The graphics show that there is no need to implement system optimal routing strategy at the initial stage of the incident. However, it is critical to use system optimal routing strategy as freeway and arterial are getting congested and the queue delay in freeway increase.

It is evident that the total travel time reductions are high since 100% user compliance and 100% market penetration are assumed. It is noted that if only user equilibrium routing strategy is implemented, the total travel time reductions will be decreased because of the 'Breass Paradox'.
Figure 4.5 The change of travel time saving ratio during the incident

(incident duration: 30 min, freeway demand: 2500vph, arterial demand (see legend))
Figure 4.6 The change of travel time saving ratio during the incident

(incident duration: 60 min, freeway demand 2500vph, arterial demand (see legend))
Figure 4.7 The change of travel time saving ration on the process of incident

(incident duration: 30 min, freeway demand: 3000 vph, arterial demand (see legend))
Figure 4.8 The change of travel time saving ratio during the incident

(incident duration: 60 min, freeway demand: 3000vph, arterial demand (see legend))
Figure 4.9 The change of travel time saving ratio during the incident

(incident duration: 30 min, freeway demand: 3500vph, arterial demand (see legend))
Figure 4.10 The change of travel time saving ratio during the incident

(incident duration: 60 min, freeway demand: 3500 vph, arterial demand (see legend))
CHAPTER 5

STRATEGY EVALUATION

The evaluation of adaptive routing strategies for DRGS is presented by the utilization of a dynamic simulation model for Intelligent Transportation System (ITS), INTEGRATION under various non-recurrent congestion. The adaptive routing strategy is applied to the traffic diversion under non-recurrent congestion situation. The following alternative strategies for DRGS are evaluated:

(1) Diversion by the Adaptive Routing strategy.

(2) Diversion by the Instantaneous User Equilibrium Strategy

The Adaptive routing strategy employs traffic conditions during the occurrence of an incident and other road environment conditions to recommend efficient and effective diversion routes, while the user equilibrium strategy uses a real-time minimum travel time path for individual driver. In other words, the user equilibrium strategy unlike the adaptive routing strategy does not take into account the total system travel time saving in selecting diversion routes.

The comparison of the two methods were achieved by simulating various incident scenarios using the idealized network and Fairfax county road network. Several incident conditions by incident duration and traffic demand on freeway and arterial were investigated using each of the strategies. The simulation tool employed in the study is the INTEGRATION traffic simulation model.
The following section overviews the INTEGRATION simulation package and description of the study input file. Further, the simulation runs and results have been summarized.

5.1 The INTEGRATION Simulation Model

5.1.1 Overview

INTEGRATION is one of the promising traffic simulation models developed by Dr. Van Aerde and Transportation Systems Research group in Queen's University. It is capable of analyzing traffic flow in terms of vehicles which can be modeled as individual entities. The model has the ability to simulate and optimize integrated freeway/arterial road networks of up to 10,000 links with ATMS and ATIS features including:

- geometric and traffic control features such as signalized intersections, ramp meters, HOV lanes and CMS etc.
- definition and simulation of multiple incidents
- optimization of fixed and real-time controls such as traffic signal and ramp meters.
- evaluation and reflection of different route selections for a variety of vehicle types
- representation of motorist biases and restrictions, motorist advisory and in-vehicle route guidance system.
- incorporate graphic network representation which provides a current indication of vehicle movement distinguishing freeflow, over capacity, and stand queue states.
The INTEGRATION simulation software has recently been applied with success in the
design the following systems:

- TRAVETEK in Orlando, Florida
- SMART Corridor in Santa Monica, California
- COMPASS in Toronto, Ontario
- FHWA ITS Architecture Study

Inputs into INTEGRATION include the following:

- Network structure - links/nodes
- Link controls - # of lanes, freeflow speed, saturation flow, lengths
- Network controls - signal timings, ramp metering rates, etc.
- Demand data - O-D travel patterns, portion of each driver class
- Incident data - Start time, duration, severity, location.
- Control characteristics - biases and level of compliance

Outputs from INTEGRATION include:

- Vehicle speed, travel times, delays, V/C ratio, stops
- Average Trip lengths, average occupancy
- Signal timing optimization
- Fuel consumption and emissions
- On-screen graphic display of vehicle movements, queues, controls and incidents

Vehicle probe reports
Further detailed understanding of the INTEGRATION software could be obtained from (reference number).

5.1.2 Special Features of INTEGRATION

1) Driver Class
   - The different driver class can be modeled in INTEGRATION to represent different routing behavior or different privileges to travel time information for each class of drivers.
   - There are five driver classes in INTEGRATION (see Table 5.3)

2) Changeable Massage Sign (CMS)
   - The real-time data is provided to driver class I when they pass by one of CMS and/or RGS beacon site.
   - The level of compliance is specified by the fraction of driver class I that are eligible to consider re-routing on the basis of the real-time data provided by the CMS
   - The travel time information is refreshed every 3 minutes.

3) HOV Lanes
   - Each link has HOV lane variable which indicate that this link can only be utilized, in minimum path calculations, by driver class V.

4) Level of Surveillance
   - Each link is coded with the value \(0.0 \leq x \leq 1.0\) which indicate if the link is being monitored for real-time travel time data using a standard vehicle detector.
• The value will be interpreted as the probability in time of how often real-time data will be available.

5) Individual Vehicle Departures
• Each O-D pair has random headway factor \(0.0 \leq x \leq 1.0\) which indicate the portion of the vehicle headway that is random.
• The value 0.0 will result in a completely constant headway, while the value 1.0 will result in a completely random headway which follows exponential distribution with a mean of average headway.

6) Error term in link travel time
• The error term is to reflect the fact that drivers may only know the prevailing link travel times to within some margin of error.
• This may also be used to reflect the variability in individual drivers' perceptions of the true link travel time owing to limitations of surveillance equipment, discrepancies in the data fusion process, or uncertainty in the quality of the data.

5.1.3 Incident Simulation

• The incident is assumed to occur at the end of the specified link.
• The reduction of capacity is calculated in view of the effective number of lanes (real number) of traffic that are expected to be lost.
• It is possible to have multiple simultaneous incidents on the network on different links.
• It is also possible to have consecutive incidents on the same link at the same time or during overlapping time period, which will be in effect only the most severe capacity reduction.

• The type of diversion due to an incident is a function of the mix of driver classes, the travel times on any competing routes, and the level of access that drivers have to travel time information updates.

<table>
<thead>
<tr>
<th>Input</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td># of incidents</td>
<td>Integer (Maximum 5)</td>
</tr>
<tr>
<td>Location of Incident</td>
<td>Identification # of the link</td>
</tr>
<tr>
<td>Effective # of lanes, blocked by the incidents</td>
<td>Real (0.0 \leq x \leq # \text{ of lanes existing on this link})</td>
</tr>
<tr>
<td>Simulation time at which incident is to begin</td>
<td>Integer (sec)</td>
</tr>
<tr>
<td>Simulation time at which the incident is to end</td>
<td>Integer (sec)</td>
</tr>
<tr>
<td>Modeling Scale</td>
<td>Model</td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
</tr>
<tr>
<td>Macroscopic</td>
<td>FREEFLOW</td>
</tr>
<tr>
<td></td>
<td>TRANSYT 7-F</td>
</tr>
<tr>
<td></td>
<td>HCS</td>
</tr>
<tr>
<td>Mesoscopic</td>
<td>INTEGRATION</td>
</tr>
<tr>
<td></td>
<td>DYNASMART</td>
</tr>
<tr>
<td>Microscopic</td>
<td>NETSIM</td>
</tr>
<tr>
<td></td>
<td>FREESIM</td>
</tr>
<tr>
<td></td>
<td>THOREAU</td>
</tr>
</tbody>
</table>

Table 5.2 Comparison of traffic simulation models
Table 5.3 Summary of driver classes in INTEGRATION

<table>
<thead>
<tr>
<th>Driver Class</th>
<th>Driver Type</th>
<th>Information Access</th>
<th>Routing Option</th>
<th>Traffic Routing Algorithm</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Background traffic</td>
<td>no-access to real-time data</td>
<td>1</td>
<td>Static Equilibrium Assignment based on Frank-Wolfe algorithm</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Prescribed Multi-path trees which have probabilities to be selected.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>A time series of externally specified link travel times.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>A single average link travel time.</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>A single route based on free-speed travel times.</td>
<td>5</td>
</tr>
<tr>
<td>II</td>
<td>RGS equipped</td>
<td>real-time data</td>
<td>1</td>
<td>Currently available real-time network conditions which will be updated continuously</td>
<td>1</td>
</tr>
<tr>
<td>III</td>
<td>Enhanced RGS</td>
<td>real-time and anticipatory data</td>
<td>1</td>
<td>A combination of real-time link travel time and anticipatory data same as driver class II</td>
<td>1</td>
</tr>
<tr>
<td>IV</td>
<td>TravTek</td>
<td>N/A</td>
<td>N/A</td>
<td>Replicate the characteristics of TravTek vehicles</td>
<td>2</td>
</tr>
<tr>
<td>V</td>
<td>HOV</td>
<td>real-time data</td>
<td>1</td>
<td>same as routing option 2 in driver class I (including HOV links)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>same as driver class II (except that they can use HOV links)</td>
<td>2</td>
</tr>
</tbody>
</table>
5.2 Simulation with Idealized Network

5.2.1 Simulation Method

The evaluation of adaptive routing strategy for DRGS is performed with idealized network which has following configurations:

- Networks: 7 nodes and 8 links (one freeway and one neighboring arterial.)
- Freeway traffic demand: 3500 vph, 2500 vph
- Arterial traffic demand: 600 vph, 1200 vph
- Freeway capacity: 4000 vph (2000 vph/lane)
- Arterial capacity: 2000 vph (1000 vph/lane)
- Incident severity: 1 lane blockage (65% capacity reduction)
- Sensitivity analysis by incident duration (30, 60 min)

Four simulation categories have been identified by traffic demand on freeway and arterial as follows:

- Arterial Normal Freeway Normal (ANFN): Arterial V/C (0.3), Freeway demand (0.625)
- Arterial Normal Freeway Congested (ANFC): Arterial V/C (0.3), Freeway demand (0.875)
- Arterial Congested Freeway Normal (ACFN): Arterial V/C (0.6), Freeway demand (0.625)
- Arterial Congested Freeway Congested (ACFC): Arterial V/C (0.6), Freeway demand (0.875)

Figure 5.1 Idealized network for integrated traffic simulation
5.2.2. Simulation Results

Figure 5.2 shows that when the travel time saving ratio is maximum when both arterial and freeway have normal traffic demand under incident. As the demands increase, the travel time saving ratios decrease. It is noted that ACFN condition can save more total travel time than ANFC condition. This is because there is not enough capacity in arterial under ACFN condition to accommodate the system optimal routing that pursue the utilization of remaining capacity.

5.3 Simulation with Realistic Network

5.3.1 Input data and configuration of the network

The transportation network that was employed for the comparison studies is Fairfax county which is located in the Northern Virginia region. Figure 5.3 shows the location of Fairfax county within the region. The network covers 9.5 miles of i-66 freeway section and neighboring arterial.

As mentioned earlier, the INTEGRATION simulation model requires five basic inputs to describe the Fairfax county network being used for the study. These include:

- Node coordinates file
- Link descriptor file
- Traffic demand file
- Signal timings file
- Incident descriptor file
Figure 5.2 Total travel time saving by adaptive routing strategy over user equilibrium routing strategy under incident condition
5.3.1.1 Node Descriptor File

The primary purpose of the node coordinates file is the description of the x-y location of the nodes which are the start and end of each link in the traffic network. The coordinates are used to display the network and its attributes on the screen as the simulation progresses. This facilitates the correction of mistakes in coding the network. The network representation consists of 32 Origin-Destination pairs, 57 nodes and 111 links and covers approximately 9.5 miles of the I-66 freeway section. The relevant coordinate data used in this study was obtained by taking relative measurements from the county map.

5.3.1.2 Link Descriptor File

The links input data file provides attribute information of the links that join the nodes. The basic link attribute requirements consists of link length, number of lanes, saturation flow per lane and saturation flow reduction coefficient for congested conditions which is the ratio of congested saturation flow to uncongested saturation flow. Link features such as number of traffic signals controlling the link has been excluded in this analysis. This is because the effect of traffic signals has been included in the lane capacity calculations.

5.3.1.3 Traffic Demand (Origin-Destination Trip Matrix) File

The traffic demand file is coded into the model as a series of Origin-Destination flow rates which are considered to be in effect for a user-specified period of time.
Figure 5.3  The realistic network of Fairfax County in Virginia
For example, if a particular Origin-Destination trip rate remains constant throughout the simulation period, then it will be expressed as a single entry in the demand file indicating that it does not change from the start to the end of the simulation. If however, the Origin-Destination trip rates change during the course of the simulation, it is coded as a series of entries specifying the time periods that each of them prevails during the simulation. In some cases where trips are produced during a short peak time period, a high demand can be coded into the traffic demand file for a short period. The traffic demand data was synthesized from ground counts by Arvind’s algorithm. [See Arvind 1995]

5.3.1.4 Signal Timings File

The signal timings file is used for the identification of the signal control logic that is used to set or modify the signal timings at any signalized intersections or ramp meters in the network. As specified earlier, this file has been excluded from the input data, since the signal timing effects have been considered in coding the link capacities.

5.3.1.5 Incident Descriptor File

The incident descriptor file consists information on the number of incidents that are to be modeled, their severity and duration. Incidents of several different forms such as multiple consecutive or concurrent can be modeled at locations in the network or at any time during the simulation. Coding of incident severity takes the form of specifying the effective reduction in the number of lanes while the incident duration is specified in
terms of the start and end times of the incident using the master simulation clock as the reference clock. Here, four simulation by different incident duration from 15 minutes to 60 minutes is performed.

5.3.1.6 Summary of the Simulation

- Incident type: 65% capacity reduction (1 lane blockage)
- Traffic Assignment Algorithm: Fixed Multi-Path Assignment (update every 5 minutes)
- Incident duration: 15, 30, 45, 60 min (10 min ~ 70 min on simulation time)
- Total Simulation Time: 110 Min. (4.2 Hour)
- Incident locations on I-66
- Scenario I: Adaptive routing strategy
- Scenario II: Instantaneous user equilibrium routing strategy

5.3.2 Simulation Results

Table 5.4 shows that the adaptive routing strategy can reduce the total travel time within the range of 3% to 10%. As incident duration increases, the travel time saving ratio also increases.
Table 5.4 Comparison of traffic performance in realistic network

<table>
<thead>
<tr>
<th>Incident duration</th>
<th>Average trip times (min)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>User Equilibrium Routing Strategy</td>
<td>Adaptive Routing Strategy</td>
<td>Reduction Ratio(%)</td>
</tr>
<tr>
<td>15</td>
<td>15.49</td>
<td>14.96</td>
<td>3.4</td>
</tr>
<tr>
<td>30</td>
<td>17.70</td>
<td>16.69</td>
<td>5.7</td>
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<td>20.34</td>
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</tr>
<tr>
<td>60</td>
<td>23.95</td>
<td>21.43</td>
<td>10.5</td>
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</table>
CHAPTER 6

CONCLUSION AND FURTHER RESEARCH

6.1 Conclusion

The high cost of traffic congestion which runs into several billions of dollars per year in the United States behooves upon traffic and transportation professionals, the responsibility to find solutions to alleviate them. Several methods are currently being developed to address incident related traffic congestion problems which account for about 60 percent of the total traffic congestion in the United States. However, it can not be overemphasized that whichever method is developed to address the problem, it should be effective and efficient.

Currently Dynamic Route Guidance Systems (DRGS) are being expected as a promising solution to traffic congestion. This research proposed an adaptive routing strategy for DRGS as an effective and efficient methodology. The research concludes with the following findings and recommendations for further researches.

Infrastructure based DRGS have advantage of pursuing system optimal routing strategy, which is more essential under abnormal traffic conditions such as non-recurrent congestion and natural disaster. However user compliance could be a problem under such a strategy, particularly when some of equipped drivers are urged not to choose minimum travel time path for the sake of improving the total network travel time. On the other hand, In-vehicle based DRGS can utilize the user-specified route selection criteria
to avoid "Braess Paradox" under normal traffic conditions. However, it may be of little use under abnormal traffic conditions and high DRGS market penetration.

In conducting the comparative analysis between system optimal strategy and user equilibrium strategy, significant differences were found within the mid-range traffic demand. The maximum total travel time difference occurs when the level of traffic demand is half of the system capacity. At this point, system optimal route guidance strategy can save more than 11% of the total travel time of user equilibrium route guidance strategy.

According to the computation results, there is no need to implement system optimal routing strategy at the initial stage of the incident. However, it is critical to use system optimal routing strategy as freeway and arterial are getting congested and the queue delay in freeway increases.

The adaptive routing strategy is evaluated using Traffic simulation model, INTEGRATION. According to simulation results using an ideal network, the travel time saving ratio is maximum when both arterial and freeway have normal traffic demand under incident. In case of a realistic network, the adaptive routing strategy also proved to save the total travel time between 3% to 10% over the traditional user equilibrium routing strategy. The reduction of total travel time increases as the incident duration increases. Consequently, it is concluded that the adaptive routing strategy for DRGS is more efficient than using user equilibrium routing strategy alone.
6.2 Further Research

The following has been suggested as areas of further research to this dissertation.

- Sensitivity analysis with different user compliance ratio
- Sensitivity analysis with different market penetration ratio
- Sensitivity analysis with different information updating time interval
- Establishment of multiple user class optimization technique
- Application of the adaptive routing strategy to general route guidance scenarios based on radio based dynamic route guidance system
- Incorporation with incident management algorithm to implement comprehensive incident management strategy
REFERENCE


I. MATLAB PROGRAMMING FOR NONLINEAR OPTIMIZATION

1. Program for single alternate route case

```matlab
% set the data base

dist1=2;
dist2=2.0;
fspeed1=65;
fspeed2=45;
u=zeros(11,20);
s=zeros(11,20);
fcap=4000;
acap=2000;
n=2;
m=21;

for num2=1:n
    %fspeed2=fspeed2+2;
    %dist2=dist2+0.2
    a1=dist1*60/fspeed1;
    a2=dist2*60/fspeed2;
    %acap=acap+200;
    %fcap=fcap+200
    capacity1=fcap/60;
    capacity2=acap/60;
    b1=a1*(capacity1^2);
    b2=a2/(capacity2^2);

    % calculate user equilibrium
    q=0;
    xue=zeros(2,m);

    for num=1:m
        X0=[-1,1];
        options(13)=1;
        VLB=zeros(1,2);
        st='x(1)^4+x(2)^4';
        xue(1,2,num)=x;
        ue(num2,num)=total;
        q=q+5;
    end
    %xue

    % calculate system optimal

    q=0;
    xso=zeros(2,m);

    for num=1:m
        X0=[-1,1];
```

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options(13)=1;
VLB=zeros(1,2);
VUB=[];
st2=[f","num2str(a1),"x(1)"+"",num2str(b1),"x(1)*4"+"",num2str(a2),"x(2)"+"",num2str(b2),"x(2)*4"+"",g","int2str(q),"-x(x(1)-x(2));
[x,options]=constr(st2,X0,options,VLB,VUB);
xso(1:2,num)=x';
so(num2,num)=options(8);
q=q+5;
end
fcap=fcap-2000;
%xso
end
%ue
%so
xx=zeros(n,m);
%format bank
xx=ue-so;
qq=0.5:100;
dist=1:1:3;
x=10:1:100;
plot(qq,xx)
%mesh(xx)
%axis([0 100 0 3 0 60])
%title('Fig-2-6 3-dimensional plot of the differences between UE and SO')
xlabel('Total Traffic Demand (veh/min)')
ylabel('Distance of Alternate Route (mile)')
%p=interp1(qq,xx,'cubic');
%p=interp1(qq,xx,'p',4,xx)
%plot(qq,xx,'o',xx,yy)
%p=interp1(qq,xso,xx,'spline');
%plot(qq,xso,'o',xx,yy)

2. Program for multiple alternate route case

% set the data base

dist1=2;
dist2=2;
dist3=2.5;
fspeed1=65;
fspeed2=45;
fspeed3=30;
ue=zeros(3,20);
so=zeros(3,20);
fcap1=4000;
fcap2=2000;
fcap3=1000;

for num2=1:2
%fspeed2=fspeed2+2;
%dist2=dist2-0.2
a1=dist1/fspeed1*60;
a2=dist2/fspeed2*60;
a3=dist3/fspeed3*60;

capacity1=fcap1/60;
capacity2=fcap2/60;
capacity3=fcap3/60;
b1=a1/(capacity1*3);
b2=a2/(capacity2*3);
b3=a3/(capacity3*3);
% calculate user equilibrium
q=0;
% n=21
% xue=zeros(3,n);
for num=1:n
    X0=[-1,1,1];
    options(13)=1;
    VLB=zeros(1,3);
    x=zeros(1,3);
    VUB=[];
    st1='f=x(1)^2+num2str(a1)^4;x(1)^4+num2str(a2)....
         x(2)^4*num2str(b2)^4+num2str(a3)^4+num2str(b3)....
         x(3)^4+num2str(c)^4;g=x(1)^2-x(2)^2-x(3)^2;
    [x,options]=constr(st1,X0,options,VLB,VUB);
    total=q*[a1+b1*x(1)^3];
    xue(1:3,num)=x';
    ue(num2,num)=total;
    q=q+5;
end
xue
%
% calculate system optimal
q=0;
% xso=zeros(3,n);
for num=1:n
    X0=[-1,1,1];
    options(13)=1;
    VLB=zeros(1,3);
    VUB=[];
    st2='f=x(1)^2+num2str(a1)^4;x(1)^4+num2str(a2)....
         x(2)^4*num2str(b2)^4+num2str(a3)^4+num2str(b3)....
         x(3)^4+num2str(c)^4;g=x(1)^2-x(2)^2-x(3)^2;
    [x,options]=constr(st2,X0,options,VLB,VUB);
    xso(1:3,num)=x';
    so(num2,num)=options(8);
    q=q+5;
end
xso
fcap1=fcap1-2000;
end
ue
so
xx=zeros(3,n);
format bank
xx=ue-so;
qq1=0:0.5:100;
qq2=0:0.05:100;
ix1=1:len(qq1);
ix2=0:0.1:100;
jy1=interp1(qq1,xx(1,:),ix1,'cubic');
jy2=interp1(qq2,xx(2,:),ix2,'cubic');
plot(ix1,jy1,ix2,jy2)
3. Program for realistic network

% set the data base

dist1=2.4;
dist2=3.96;
dist3=3.92;
fspeed1=50;
fspeed2=40;
fspeed3=33.75;

fcap1=4500;
fcap2=1364;
fcap3=1200;

format short;

iq=0;
%iqout=0;
sumq=0;
w=0;
queue=0;
avol=1200;
decision=0
efvd=0;

sratio=0.5;
incident_duration=60+5;
a1=dist1/fspeed1*60;
a2=dist2/fspeed2*60;
a3=dist3/fspeed3*60;

capacity1=fcap1/60;
capacity2=fcap2/60;
capacity3=fcap3/60;
b1=a1/(capacity1*3);
b2=a2/(capacity2*3);
b3=a3/(capacity3*3);
% calculate user equilibrium
n=1;

delta_t=5;
rratio=0.35;
red_capacity=rratio*capacity1;
capacity=red_capacity;

% if q<red_capacity
% quit
% end

;i=0

while w>=0
%w(i)=0;
q=input('upstream demand?(vph)')
q=q/60;
a1vfo= input('demand of alt1?(vph)')

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a2fvol=input('demand of alt2?(vph)')
a1fvol=a1fvol60;
a2fvol=a2fvol60;

l=i+1;
a1=w(l)+a1-5*delta_t;

denom=delta_t/(2*capacity);

xue=zeros(3);
xso=zeros(3);

% calculate user equilibrium

X0=[-1.1.1];
options(13)=1;
VLB=zeros(1,3);
VUB=[];
x=zeros(1,3);

st1=’numstra1.*x(1)+6.8267e-06*x(1)^4’,num2str(denom),’+’
’/(x(1)+2.549e-4*(x(2)+’),num2str(a1fvol),’+’
’+5.0559e-04*(x(2)+’),num2str(a1fvol),’+’
’+6.96699*(x(3)+’),num2str(a2fvol),’+’
’+8.7111/4*(x(3)+’),num2str(a2fvol),’+’
’+xue(1)-x(3)-x(3);’;

% calculate system optimal

X0=[-1.1.1];
options(13)=1;
VLB=zeros(1,3);
VUB=[];

st2=[’numstra1.*x(1)+6.8267e-06*x(1)^4’,num2str(denom),’+’
’/(x(1)+2.549e-4*(x(2)+’),num2str(a1fvol),’+’
’+5.0559e-04*(x(2)+’),num2str(a1fvol),’+’
’+6.96699*(x(3)+’),num2str(a2fvol),’+’
’+8.7111/4*(x(3)+’),num2str(a2fvol),’+’
’+xue(1)-x(3)-x(3);’;

format short;
%q=10.10:300;
%plot(q,q);
%fsrario=q[1/(xso(1)+xso(2)+xso(3))]
a1srario=q[1/(xso(1)+xso(2)+xso(3))]
a2srario=q[1/(xso(1)+xso(2)+xso(3))]
%fsrario=q[1/(xue(1)+xue(2)+xue(3))]
a1erario=q[1/(xue(1)+xue(2)+xue(3))]
a2erario=q[1/(xue(1)+xue(2)+xue(3))]
decision=q[1/(xue(1)+xue(2)+xue(3))]

if decision(1)>0.05
%iq(1)=q*fsrario(1)
iq(1)=input('downstream inflow ?(vph)')
iq(1)=iq(1)*60;
queue(i)=input('# of queued vehicle?')
%qout(i)=input('downstream outflow ?(vpm)')
%else
%q(i)=q*fueraio()
%end

%for num=1:1
sumq=sumq+q(i)
%end

tnjd(i)=sumq/red_capacity*delta_t;
if tnd(i)<incident_duration
capacity=red_capacity;
else
capacity=capacity1;
end

w(i+1)=queue(i)/capacity
end

save total30.txt decision -ascii

save ueratio.txt fueraio aueratio -ascii
save soratio.txt fsoratio asoratio -ascii
1. Idealistic network

1.1 node file

testl Node Coordinate File - May 1995

<table>
<thead>
<tr>
<th>Node</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>s</th>
</tr>
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<tbody>
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<td>3</td>
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1.2. O/D file

QNet-4 Traffic Demand Data - February 1994

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<th>From Demand</th>
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</table>

1.3. Link file

Testl Link Characteristic File - May 1995

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<th>C</th>
<th>T</th>
<th>O</th>
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1.4 Incident file

Testl-5 Incident Data File - May 1995

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2. Realistic network

2.1 Node file

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2.3 O/D file

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2.4 Incident file

Test1-5 Incident Data File - May 1995

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1  93  2.0  600  4200
Sang-Keon Lee was born on November 6, 1963 in Chung-Joo, Korea. He entered Yonsei University at Seoul in 1982 and received a Bachelor of Science Degree in Architectural Engineering in 1986. He continued his graduate study at Yonsei University and received a Master of Science Degree in Urban Planning in 1988. After military service, he started his research career in transportation with the Korea Research Institute for Human Settlements (KRIHS) in 1989. After working as a transportation planner for four years, he came to Virginia Polytechnic Institute and State University to pursue his Ph.D. degree in transportation engineering in August 1993. During his doctoral study, he has worked for Intelligent Transportation Systems (ITS) related projects at the Center for Transportation Research which is one of three ITS Research Centers of Excellence in USA.

After completion of his degree in 1996, Sang-Keon Lee will return to his country. He hopes to become an expert in intelligent transportation systems.