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**CALIFORNIA PATH PROGRAM  
INSTITUTE OF TRANSPORTATION STUDIES  
UNIVERSITY OF CALIFORNIA, BERKELEY**

## **The Role of Advanced Traveller Information Systems in Incident Management**

**Haitham Mohammed Al-Deek**

**PATH Research Report  
UCB-ITS-PRR-92-12**

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

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# **THE ROLE OF ADVANCED TRAVELLER INFORMATION SYSTEMS IN INCIDENT MANAGEMENT**

**BY**

**Haitham Mohammed Al-Deek**

## **ABSTRACT**

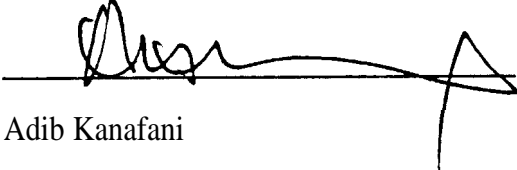
Advanced traveller information systems (**ATIS**) have been proposed recently as a promising technology for improving the efficiency of urban transportation networks and reducing traffic congestion. This dissertation deals with an important application of **ATIS** technology: the management of incidents.

An off-peak incident is analyzed using deterministic queueing methods in an idealized corridor composed of two routes. A user equilibrium strategy is implemented to disseminate real time traffic information to vehicles equipped with **ATIS**. The findings show that a few cases of queue evolution result when **ATIS** is used under incident conditions. Both the proportion of guided traffic and the incident duration play an important role in determining which case results. When an incident occurs, **ATIS** will divert all equipped vehicles to the alternate route until equilibrium is achieved. Equilibrium is maintained by reducing the rate of diversion from one route to the other through pulsed diversion of **ATIS** equipped vehicles. The implication is that during equilibrium some **ATIS** equipped vehicles will be diverted to an alternate route while others will remain on the route where the incident has occurred.

The user benefits follow similar characteristics for all the cases studied. Guided traffic is better off than unguided traffic only during the diversion period that precedes equilibrium, but this advantage is drastically reduced when a queue forms on the alternate route or where equilibrium can be achieved. System benefits increase with the fraction of guided traffic as long as it is below the critical value that causes a queue on the alternate route, but system benefits saturate when this value is exceeded. Also, system benefits do not increase with the proportion of guided traffic in cases where equilibrium can be

achieved The critical fraction does not depend on the incident parameters but does depend on two corridor parameters: the capacity of the alternate route and the corridor demand. The critical fraction equals zero when there is no alternate route and equals one in corridors with several major arterials, usually parallel to the main facility, that can absorb the corridor demand without being congested.

The study findings suggest that route guidance has a significant role in the management of incidents during the off-peak period, when **uncongested** alternate routes are likely to be available. During the peak period, however, the alternate routes are usually congested, and consequently there is a need to spread traffic over time rather than space. This can be achieved through departure time switching rather than route switching. Here, the role of **ATIS** is thought to be more useful before starting a trip rather than en-route. Pre-trip traffic information permits the most flexible decisions by trip makers. Travellers can switch routes, departure times, and possibly modes. This area is yet to be investigated and is an interesting subject for future research.



A handwritten signature in black ink, appearing to read 'Adib Kanafani', is written over a horizontal line. The signature is fluid and cursive, with a long horizontal stroke and a vertical stroke at the end.

Adib Kanafani

**Chairman** of Committee

To Kouther, Jumana, and Abdullah

**THE ROLE OF  
ADVANCED TRAVELLER INFORMATION SYSTEMS  
IN INCIDENT MANAGEMENT**

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by

Haitham Mohammed Al-Deek

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## 1. INTRODUCTION

The objective of this research is to explore conditions under which route guidance information is useful in incident management and to estimate its benefits.

Advanced traveller information systems (**ATIS**) have gained worldwide interest as a promising technology for improving the efficiency of urban networks and reducing congestion. It is generally anticipated that the provision of route guidance to travellers will help them avoid congested links in the network, thereby reducing congestion by spreading traffic over space, and possibly time. This proposition has been so well received that technology for **ATIS** is being developed and tested in numerous locations around the world. There remains, however, a paucity of analysis to demonstrate that the implementation of **ATIS** will in fact have a significant impact on congested urban networks, and to estimate the magnitude and distribution of its potential benefits. This research is concerned with an important application of **ATIS** technology: the management of incidents. Using an idealized traffic corridor and deterministic queuing methods, conditions under which route guidance information is useful are identified. Benefits to traffic guided with **ATIS** are estimated and system performance is evaluated in diverse environments of non-recurring congestion.

This research provides a fundamental basis for understanding the benefits of **ATIS**, with relevant implications for public and private sector implementation of **ATIS** as a mean of reducing incident caused congestion.

### 1.1 Incidents and Incident Management

An incident is a random event that occurs on a section of roadway and affects its capacity. These unexpected events can be traffic accidents, disabled vehicles, spills, and other environmental problems. Congestion results whenever roadway capacity is reduced



below the level of demand. Some of the parameters that influence the impact of an incident are: incident duration, reduction in roadway capacity, and travel demand level during the incident.

Incidents are viewed as a major problem in urban travel because they cause unexpected delays for motorists. Truck-related incidents usually have a larger impact than other incidents. It was estimated that in 1987 an average of 19 truck incidents per weekday occur on the u-i-county freeway system in Los Angeles, Ventura, and Orange Counties in California. The majority of these incidents (15 per day) occur on the heavily traveled freeways of Los Angeles County (Recker, 1989). The duration of these incidents ranges from forty minutes to about two and a half hours. A recent study of Los Angeles, San Francisco, and San Diego has shown that 80% of all truck-related incidents occur during daytime and about 50% of all incidents occur during midday off-peak period (Cambridge Systematics, 1988; Reilly and Haven, 1989).

A nationwide study, Lindley (1987) estimated that incident congestion constitutes more than one half of the total congestion on U.S urban freeways. Empirical work has shown that lane-blocking incidents have a more than proportional impact on freeway capacity. For example, the blockage of a single lane on a three lane freeway reduces freeway capacity by 50% (Lindley, 1986).

A look into the future offers little hope that things will get better. A. D. May (1989, p.41) concluded:

Congestion today in our urban areas is severe and over the next 15-20 years the congestion will be so severe as to significantly limit growth in automobile registration and usage. Non-recurring congestion will grow at even a faster rate than recurring congestion, and motorists will encounter congestion at unexpected locations and periods of time.

On the supply side, the picture is not encouraging either. The number of miles of new highways being constructed each year is significantly lower than in past years. The

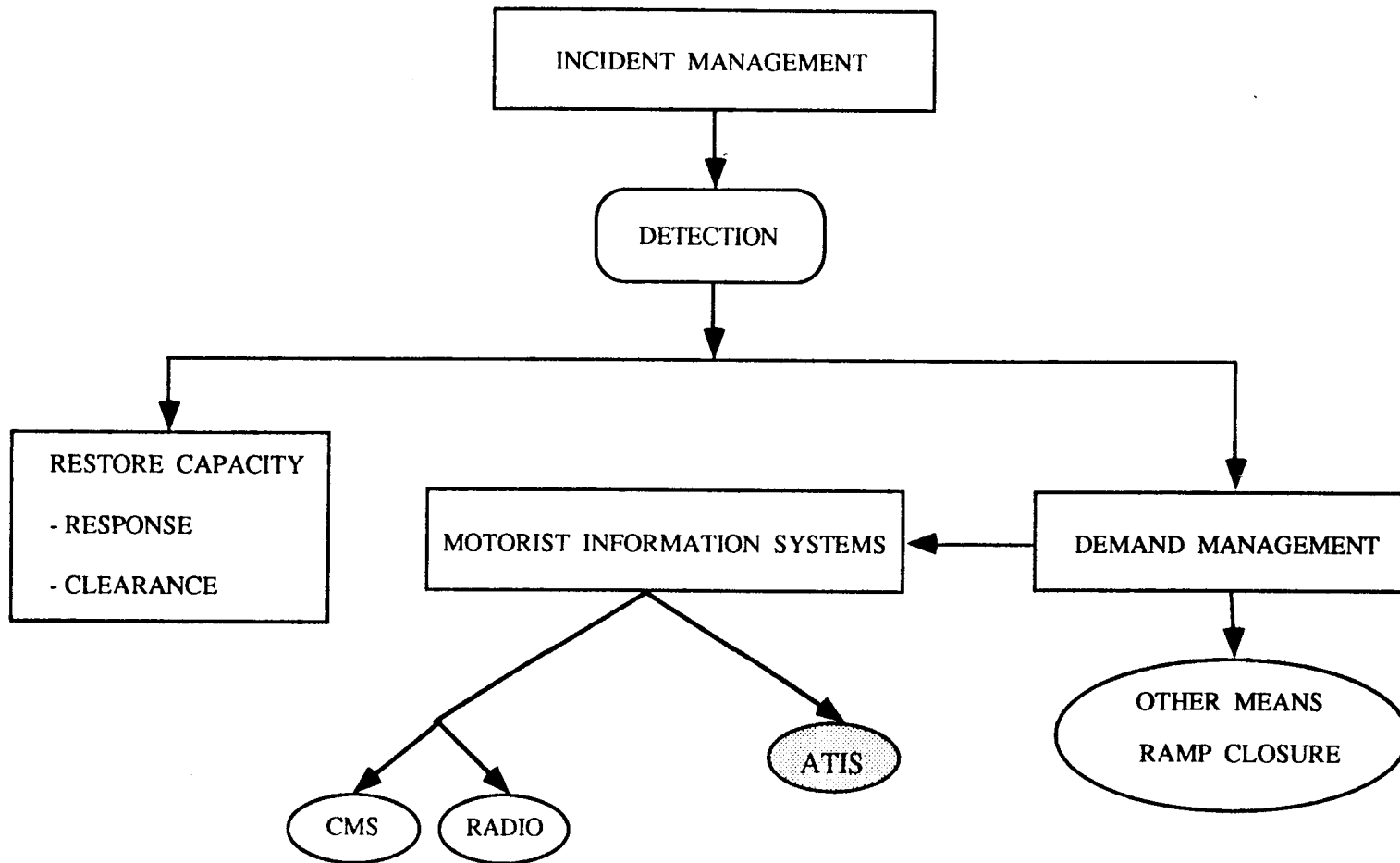
cost of building or widening freeways has escalated during the past few years. Thus, the major effort over the next decade will be given to improved use of the existing highway system through congestion management.

The incident management process is shown in Figure 1.1. Once, an incident is detected, incident management follows two parallel processes: restoration of normal capacity through incident response and clearance, and demand management through motorists information systems and other means such as freeway ramp closures. A detailed description of research work on incident detection, response, and clearance can be found in Mannering and Jones (1990). Despite the advancements in incident response and clearance, fast removal policies are difficult to implement because of liability issues, and the multitude of public and private agencies and groups involved. The issue of liability is especially of concern when valuable commercial loads or hazardous materials are involved. Also there may be other priorities at the incident scene such as injuries, fire, and accident investigation, and managing traffic might not be at the top of the list. Thus, this research focus is on incident management using advanced **traveller** information systems.

## **1.2 The Concept of ATIS**

The concept of **ATIS** is to collect and analyze data on the current performance of the highway system, and to derive information that can be disseminated to travellers on a real time basis.

Information may be delivered to travellers before they start a trip or while en route. Real time traffic information can be delivered to travellers en route via two means: 1) outside the vehicle, or 2) inside the vehicle. Information delivered outside the vehicle is visual, as in the case of changeable message signs (CMS). Information delivered inside the vehicle may be visual, or it may be audio, or both, e.g Highway Advisory Radio (**HAR**) and in-vehicle **ATIS**. Although there are other uses of **ATIS** such as emergency



CMS: CHANGEABLE MESSAGE SIGNS

FIGURE 1.1 INCIDENT MANAGEMENT

communication and parking availability information, the main focus of this study is on the use of **ATIS** in route guidance.

There is a variety of in-vehicle **ATIS** models such as the Japanese **AMTICS** (Advanced Mobile Traffic Information and Communication Systems) (Tsuwawa and Okamoto, 1989), the German LISB (Driver Guidance and Information System) (Sparmann, 1989), and the British **AUTOGUIDE** (Catling and Belcher, 1989). Some other systems are also described in Garrison (1986) and Ygnace (1990). Despite this worldwide interest and the expectation that route guidance systems will be in use by mid-1990s (see, for example, Boyce, 1988, 1989; and Ben-Akiva and de Palma, 1989) the most advanced of these systems are still in an experimental stage.

### **1.3 ATIS Versus Conventional Motorists Information Systems**

One may question the need for **ATIS** especially if it is possible to disseminate traffic information to drivers via cheaper means which already exists such as Changeable Message Signs (**CMS**) and Highway Advisory Radio (**HAR**). Commuter surveys indicate that both **CMS** and **HAR** have serious deficiencies and limitations, (see, for example, Shirazi, 1988, and Haselkom and Bat-field, 1990). Incidents may occur at any location in the network and it is not economically feasible to install changeable message signs at every possible junction in the network. Furthermore there are a lot of complaints about changeable message signs being vulnerable to weather conditions and need of frequent maintenance as often as every two weeks (**Haselkorn** and Barfield, 1990). More important than that are the complaints of drivers that the message is often not up to date and comes too late for anyone to make a decision. Also messages on **CMS** might be difficult for some people to read. The message usually instructs drivers to use the next few exits of a freeway and divert to some alternate routes which drivers may not know very well. When information is disseminated to all drivers to divert to an alternate route this may cause congestion on the alternate route as

well. Because of ‘this, drivers who divert may have their travel time increased and eventually will end up distrusting the system

Highway Advisory Radio has the disadvantage of sending information that is often irrelevant to drivers’ specific trips. Sometimes drivers have difficulty in retaining what they have heard **from** HAR. Many incidents broadcast by radio are minor incidents that do not take a long time to be cleared. Travellers listening to such broadcasts may choose an alternate route that could take a longer time than the route where the incident has occurred. Although such travellers might benefit others by not choosing the route where the incident occurred, they may themselves incur a loss. It is no wonder then that only a very small percentage of drivers care to listen to HAR (Haselkorn and Barfield, 1990).

Another advantage of in-vehicle **ATIS** over conventional systems is that equipped vehicles can function as traffic probes. On-board equipment stores records of average travel times for the network by link and time of day. Once there is a sufficient number of equipped vehicles, link travel times can be predicted over short time intervals and incidents can be detected rapidly.

#### **1.4 Urban Transportation Planning System and ATIS**

The introduction of **ATIS** as part of a larger package of technologies, termed “Intelligent Vehicle and Highway Systems (IVHS)“, is expected to have important implications for the Urban Transportation Planning System (UTPS). Quoting Kanafani (1991, p.1):

“The implementation of **IVHS** technologies such as **ATIS** is likely to have immediate short run effects on traffic behavior initially by altering route choice, and eventually trip scheduling and possibly destination choice. However, the most profound impacts of **ATIS** will occur in the longer term and are likely to impact travel demand. The more profound effects of **ATIS** are likely to be in trip generation, trip scheduling, trip chaining, and mode choice”.

Thus, the introduction of **ATIS** is likely to affect not only route choice, -but the entire structure of the urban transportation planning system (**UTPS**). This initiates a need to modify the classical **UTPS** framework and to come up with a revised planning analysis package that is integrated with **IVHS** technologies such as **ATIS**. The classical **UTPS** framework is composed of a sequence of travel choices as shown in Figure 1.2. First, a decision is made of whether to make a trip or not; second, a trip destination is chosen; third, a trip mode is chosen where choice of the trip mode is conditional on the chosen destination; and finally modal trips are assigned to routes that connect trip origins and destinations. When **ATIS** is available, routes that are heavily congested are dropped out of the route choice set. This is expected to influence the mode choice set by dropping out modes which are committed to the routes that are dropped out. If all the routes leading to a destination are congested (**e.g** during peak hour travel), then a traveller may think of changing the trip destination or ultimately may choose to cancel the trip. The introduction of **ATIS** suggests using an alternative approach to modeling travel demand in which the modeling sequence in **UTPS** is reversed, as shown by the shaded arrows in Figure 1.2. The reversed sequential approach to modeling travel demand has been explained in detail in Kanafani (1983, pp. 98-105).

This research is a start of the **UTPS** revision process. Immediate short run effects of **ATIS** which influence route choice under incident conditions are evaluated. Economic analysis includes the evaluation of user and system benefits of **ATIS** and analysis of the distribution of benefits for guided and unguided traffic. The benefits are measured as reduction in delay and delay related costs such as vehicle operating costs. Economic analysis is not limited to the evaluation of benefits and costs of implementing the **ATIS** technology, but can also be extended to include demand analysis and marketing research of **ATIS**. In order to perform economic analysis successfully, however, it is necessary to understand how **ATIS** functions in diverse congestion environments.

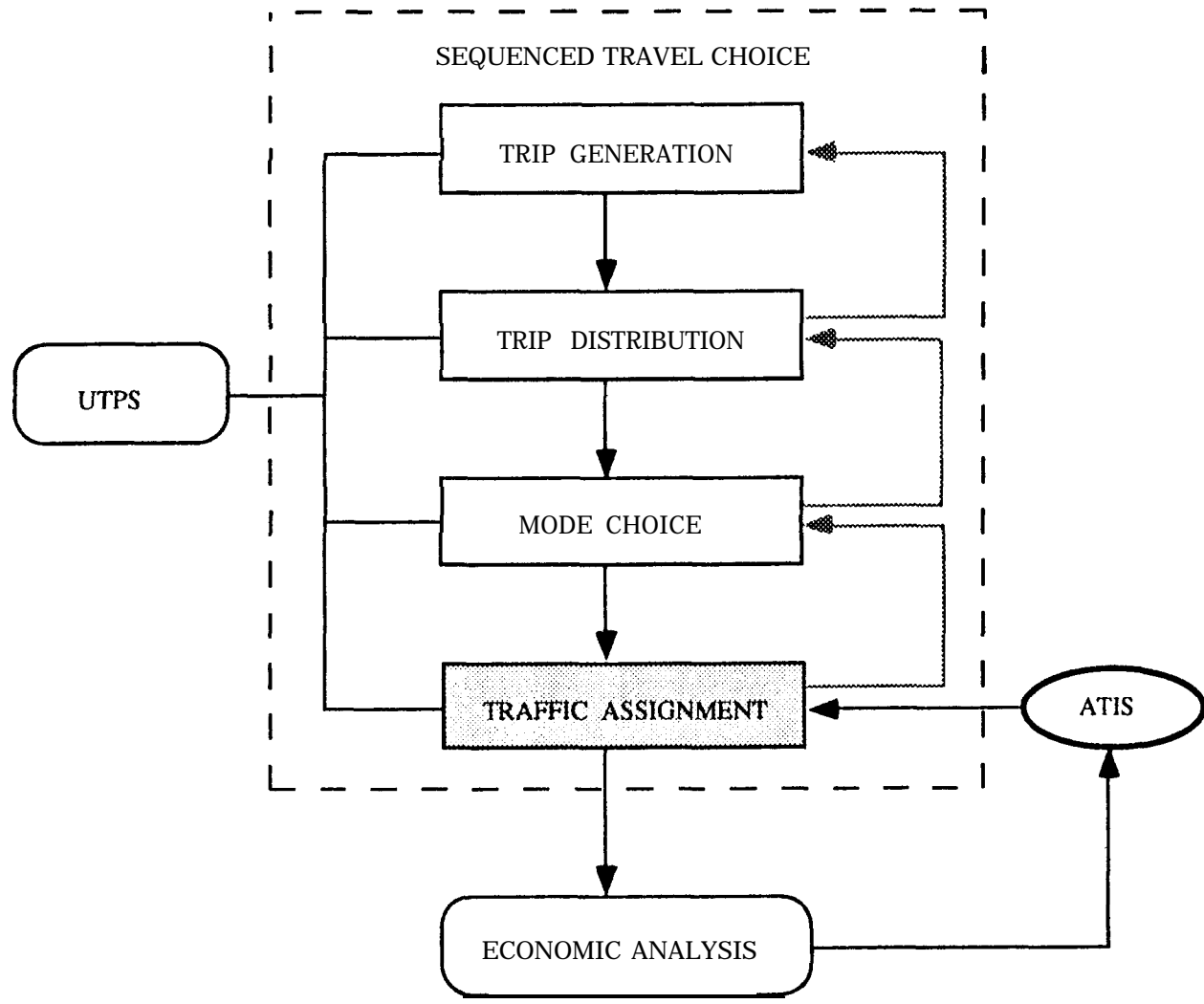


FIGURE 1.2 INCORPORATION OF ATIS TECHNOLOGY IN UTPS

## 1.5 Previous Studies

There have been numerous efforts to evaluate the benefits of dynamic route guidance information provided by **ATIS**. These efforts have been: field testing and predictive modeling and computer simulation.

### **ATIS Experiments**

The objective of the experiments is not only to evaluate the benefits of **ATIS** but also to test the system under conditions close to reality, to prove its technical feasibility, and to investigate driver acceptance. The **first** experiment of route guidance systems was the Japanese (CACS) system that began in 1979 (Yumoto et al., 1979). About 330 test vehicles were used in the experiment. In about 1000 trials it was found that reduction in mean travel time between seven selected origin-destination pairs in Tokyo was 9-15%. The second experiment was the LISB system which began in Berlin 1989 and is currently ongoing. The AUTOGUIDE system in the UK has reached the stage of field testing (Catling and Belcher, 1989). Currently, three demonstration programs are being implemented or are underway in the United States: the Pathfinder Project in the Los Angeles SMART corridor, the Travtec project in Orlando, and the Illinois Dynamic Route Guidance Experiment, (Boyce, 1990).

There are two main facts that apply to all of these experiments: first, they cost several million dollars to implement (some have cost \$40-\$50 million); and second, the fraction of vehicles equipped with **ATIS** is exceedingly small and typically is less than 1% of the traffic flow. This suggests that in order to predict the full effect of larger scale **ATIS** researchers will have to turn to predictive models.



## **Previous Research on Modeling the Benefits of ATIS**

Almost every experiment mentioned above was preceded by some effort of modeling. Kobayashi (1979) in the context of the CACS project developed a simulation model to examine the effectiveness of alternative guidance methods and applied it using data from a pilot area in Tokyo. The results indicate that total travel time in Tokyo, with the introduction of **ATIS**, could be reduced by 6% and fuel consumption by 5%.

Tsuji, et al. (1985) applied a mathematical model that they developed to a case study in the area of Tokyo. They found that guided vehicles could save up to 11% of their travel time. They assumed that the traffic flow of guided vehicles does not affect the remaining traffic flow. This assumption can be valid only if the proportion of guided traffic is very small.

After several years of research at the Transport and Road Research Laboratory (TRRL), Jeffery et al. (1987a,b), combined the results of Tsuji, et al. (1985) and the earlier results on the benefits of static route guidance information found in Jeffery (1981 a,b), and concluded that **ATIS** can achieve an average benefit of 10%.

Kanafani (1987) assessed the current level of highway navigation and route guidance technology. He concluded that the state of the art in information technology provides opportunities for application of advanced **traveller** information systems, but little is known about the potential gains that **ATIS** can offer for the relief of congestion.

Al-Deek, et al. (1988, 1989a,b) estimated the potential benefits of in-vehicle **ATIS** in the context of the PATHFINDER project. They simulated existing and incident induced traffic conditions along the Santa Monica freeway (SMART) corridor in Los Angeles. They assumed that the fraction of vehicles equipped with **ATIS** is small such that travel times on the city streets are not affected by diversion. Travel time savings for guided traffic were found to be insignificant under recurring congestion conditions while savings

were in the order of 10 minutes for a 40 minute trip (or 25%) under incident induced conditions.

The results of the previous studies are site specific and cannot be generalized to other geographical areas or other network conditions. The models used in these studies cannot analyze the sensitivity of benefits to an important variable, the fraction of vehicles equipped with **ATIS**. Furthermore, analysis of the distribution of benefits between guided and unguided traffic has not been addressed. Apparently most of the previous studies were concerned about figure estimates of benefits of **ATIS** without referring to conditions and cases under which these benefits can be achieved.

Al-Deek and Kanafani (1989c), and Kanafani and Al-Deek (1991), used a continuum approach in an idealized corridor to study the benefits of **ATIS**. The benefits were measured by comparing system optimal assignment, achieved by **ATIS**, with user equilibrium, which was assumed to occur in the absence of **ATIS**. The study demonstrated the potential benefits of **ATIS** under diverse environments of recurring congestion and identified some cases where **ATIS** is of marginal benefit and other cases where it is of no use.

## **1.6 Research Needs**

The results to date suggest that, by and large, the benefits of route guidance are marginal under conditions of recurring congestion. Experienced travellers, who make up the major portion of traffic in congested urban networks, have sufficient information to manage their **route** choice under conditions of recurring congestion. This has often been reflected in the estimates of potential benefits from **ATIS** in the vicinity of 10% savings in total travel time. These results suggest that **ATIS** is likely to be more useful under conditions of non-recurring 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 vis-a-vis the rest of the network would leave the traveller insufficiently informed to make appropriate route choice decisions. Furthermore, by extending **ATIS** information to potential travellers long before they approach incident locations, it may be possible to further reduce potential congestion by altering trip patterns, including departure times, thereby spreading traffic over time as well as space.

Real time traffic information may also be used as a control variable to “direct” travellers towards path choices closer to system optimal solution in which the total cost of travel for all trips in the network is minimized. Several strategies can be used to disseminate real time traffic information to guided travellers under incident conditions. There is a need for developing a model which can evaluate system performance and estimate the distribution of benefits (or disbenefits, if any) between guided and unguided traffic when a strategy is applied.

## **1.7 Research Objectives**

The goal of this dissertation is to establish a fundamental basis for the evaluation of the benefits of **ATIS** in generic environments of non-recurring congestion. For this purpose, a deterministic queueing model is developed and applied to an idealized corridor. The primary questions addressed by this research effort are:

1. Under what incident conditions is information useful to travellers and to the system?
2. How are the benefits distributed between guided and unguided users?
3. How sensitive are the benefits to the fraction of vehicles equipped with **ATIS**, to incident parameters, and to network parameters?

The research framework is addressed in the next chapter along with a model that analyzes the benefits of **ATIS** route guidance under incident conditions. The model is applied to an idealized corridor and cases of queue evolution are presented in Chapter 3.

Analysis of the **benefits** for this model when applied to the idealized corridor are presented in Chapter 4. A discussion of the model enhancements and extensions is provided in Chapter 5. The results are summarized and presented with recommendations for future work in Chapter 6.

## 2. RESEARCH FRAMEWORK

In order to assess the benefits of **ATIS** in incident management a suitable traffic assignment technique that can capture the special features of **ATIS** is needed. Although there is a vast literature that deals with traffic assignment techniques, little is known about the impact of **ATIS** technology on route choice and traffic assignment under incident conditions. The introduction of **ATIS** adds new requirements to modelling traffic assignment. This chapter presents a brief review of pertinent requirements for modelling traffic assignment in networks with **ATIS**. It also presents the research framework and provides a description of some generic environments where the benefits from **ATIS** are evaluated.

### 2.1 Requirements for Traffic Assignment Models with **ATIS**

The introduction of **ATIS** is expected to influence the traveller's route choice. This stimulates traffic demand for various types of the network links. Incidents cause continuous changes in the capacities of the links. The continuous changes in demands and capacities of the links lead to dynamic equilibrium between the alternative routes in the network. Consequently, the traffic assignment technique for networks under incident conditions, where **ATIS** is available, needs to model these dynamic equilibrium conditions. The traditional practice of steady-state equilibrium analysis is to assume that demand and capacity are constant over long periods of time such as the entire peak period. Even if **ATIS** is not present, it is still unrealistic to use traditional analysis techniques to model networks under incident conditions.

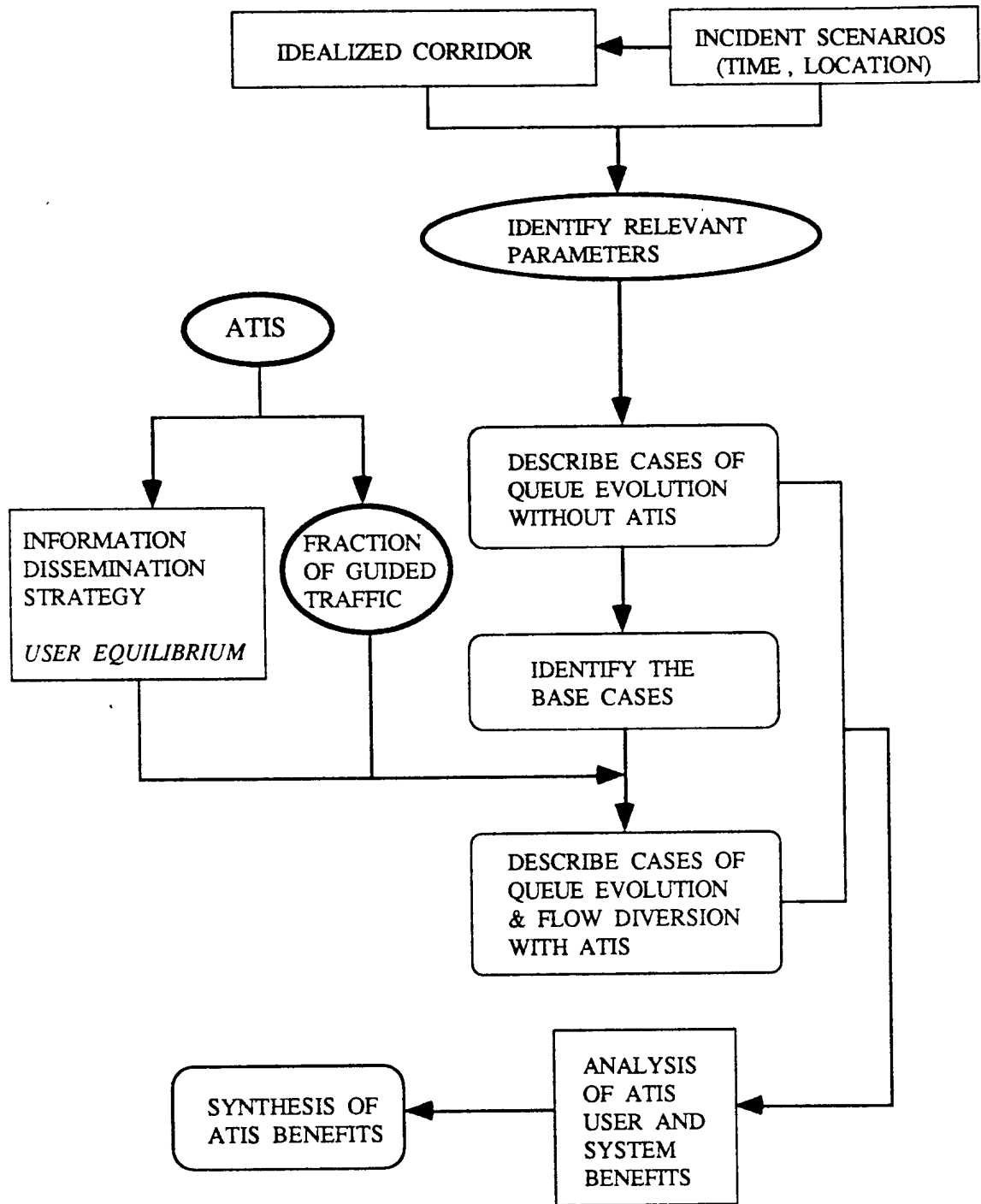
When demand exceeds capacity vehicles are stored in queues. The assignment technique should consider queueing delays on network links.

The **assignment** technique needs to have the capability of handling a non-homogeneous system with a mixture of vehicles equipped and unequipped with **ATIS**. Under incident conditions, travellers equipped with **ATIS** will be better informed of conditions of the alternate routes than unequipped travellers and will have the privilege of **choosing** the shortest route. Unguided travellers do not have access to real time **traffic** information, and therefore continue to choose routes on the basis of their non-incident experience.

An approach has been suggested recently by Van Arde and Blum (1989) to handle the problem of **traffic** assignment with route guidance. The approach utilizes microscopic computer simulation to track every vehicle as it proceeds in the network and updates routing of vehicles based on real time traffic conditions. Although this approach might be more suitable for real life applications, it requires gathering data for a large number of parameters and is therefore an extensive and expensive process.

## 2.2 Research Approach

The main **objective** of the dissertation is to explore conditions under which route guidance information is useful in incident management and to evaluate its benefits. Figure 2.1 shows the research framework and the procedure to synthesize these benefits. The research approach uses deterministic queueing methods to predict dynamic queue evolutions and traffic flow diversion in an idealized corridor under incident conditions with and without **ATIS**. The use of deterministic queueing methods in the analysis of traffic engineering **problems** is by no mean new (see, for example, Moskowitz and Newman, 1963; May and Keller, 1967; and Newell, 1982). However, these methods have never been applied to the analysis of networks under incident conditions with **ATIS**. The idealized corridor provides a generic environment where the occurrence of incidents varying in location, duration, and severity are simulated. The advantage of using this



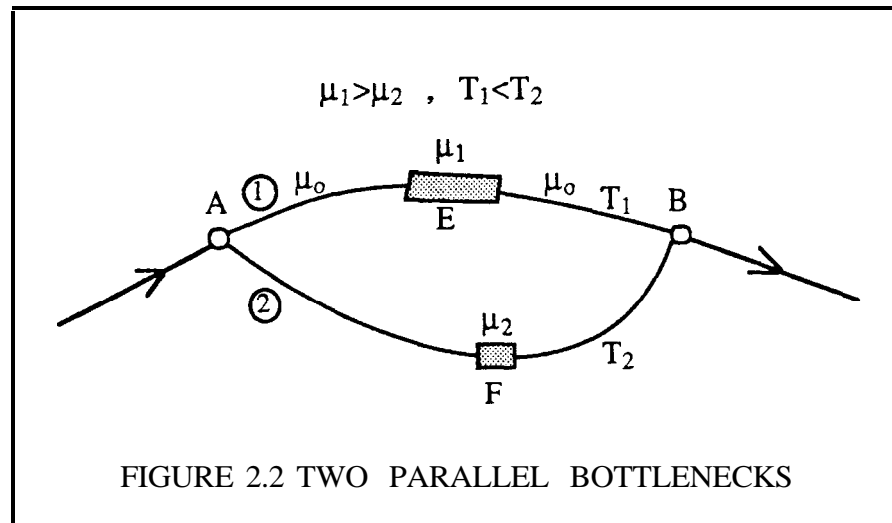
*NOTE: THE BASE CASES ARE THE CASES WHERE ATIS IF PRESENT CAN BE USEFUL*

FIGURE 2.1 RESEARCH FRAMEWORK

approach is to keep the number of problem parameters at a minimum by considering only relevant ones: the fraction of vehicles equipped with **ATIS**, incident parameters, link parameters, and traffic demand level. In the following paragraphs we describe in detail elements of the research framework

### 2.3 Idealized Corridor and Assumptions

We consider a simple corridor as shown in Figure 2.2. The corridor consists of two routes connecting points *A* and *B*. The first route is a freeway which has a bottleneck *E* with capacity  $\mu_1$ . A queue forms upstream of bottleneck *E* on this route whenever traffic demand exceeds capacity,  $\mu_1$ . The capacity of the rest of Route 1 is equal to  $\mu_0$ , which is higher than  $\mu_1$ .



Route 2 is an alternate high speed road that is longer than Route 1 and has a bottleneck *F* with capacity  $\mu_2$ , where  $\mu_2 < \mu_1$ . When there is no queue, travel time from *A* to *B* is equal to  $T_1$  on Route 1 and  $T_2$  on Route 2, where  $T_1 < T_2$ . It is assumed, following Kuwahara and Newell (1987), that these times are independent of flow except under queueing conditions. Also the empirical work by Hurdle and Solomon (1986) has shown



that freeway travel speed is independent of traffic flow until the capacity of the freeway is reached. Thus, in the absence of queues, Route 1 is always preferred to Route 2.

It is also possible to consider other configurations of Route 2 such as:

- (1) Route 2 is a frontage road or an arterial with limited capacity  $\mu_2$  that does not allow high speed, or
- (2) Route 2 is a composite of city streets with very large capacity and high speed is also not allowed.

In the real world major travel delays occur at bottlenecks. The corridor configuration described above has two parallel bottlenecks, usually there are not many bottlenecks in a real life network. Also, the number of alternate routes in a corridor that can be operationally and institutionally feasible for the purpose of traffic diversion is limited, and is in the range of one to five (JHK & Associates, 1990).

In simulating the application of ATIS technology, we assume that it is possible to estimate the flow and the travel time on each link in the network using data collected on a continuous basis via traffic surveillance. It is also possible to detect the occurrence of an incident, to estimate its duration and the capacity reduction caused by it. It is assumed in this analysis that vehicles with ATIS will always follow directions to divert to a shorter route. This assumption is not necessary for the model used here and can be easily relaxed and the consequences of relaxing it are discussed in Chapter 3.

## 2.4 Incident Scenarios

For the purpose of this research incidents are classified as either peak or off-peak incidents. The difference between the two types is discussed below.

### Peak and Off-Peak Incidents

Cumulative arrivals and cumulative departures by time "t" for a single bottleneck are

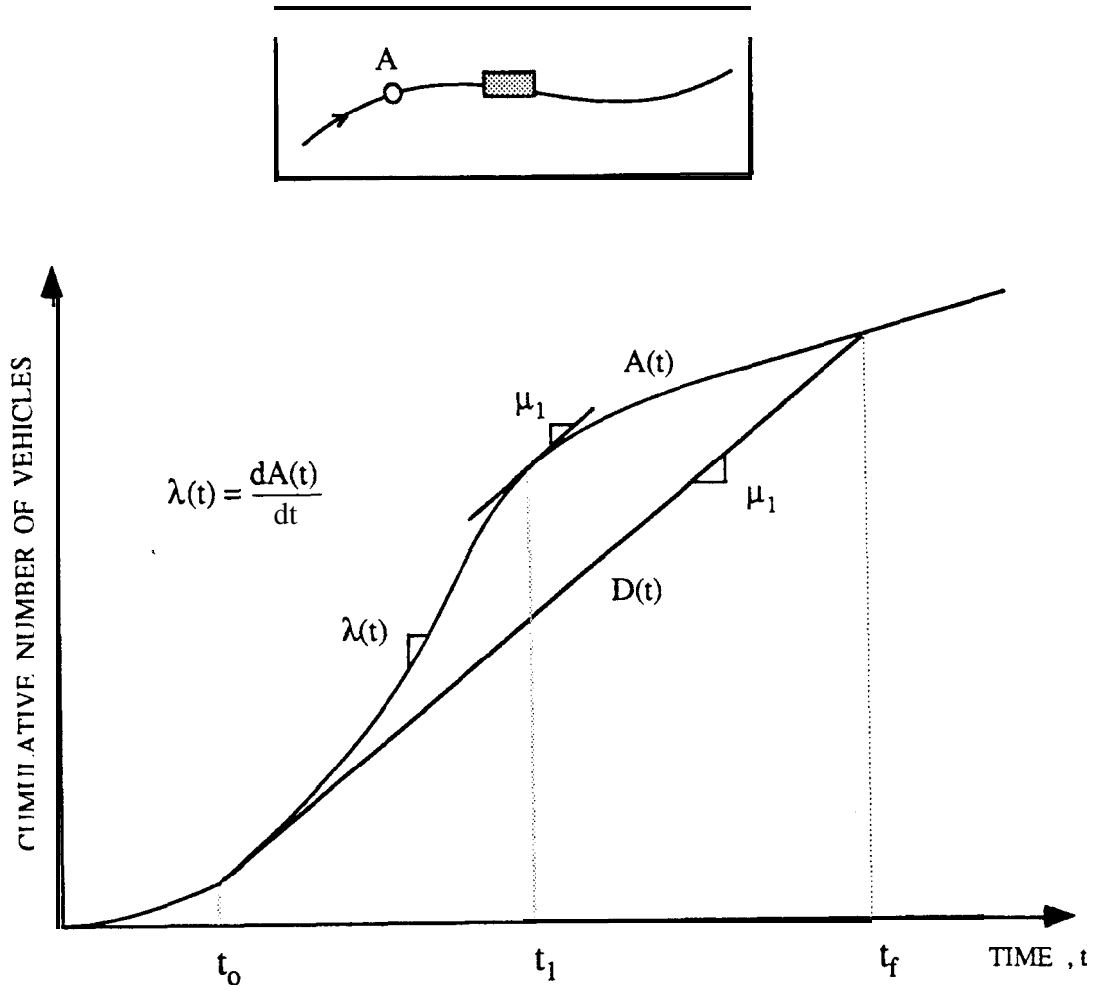


FIGURE 2.3 CUMULATIVE ARRIVALS AND DEPARTURES FOR A SINGLE BOTTLENECK

given by the curves labeled  $A(t)$  and  $D(t)$  respectively in Figure 2.3 (May and Keller, 1967, p. 118). Peak conditions are defined as conditions where demand exceeds capacity. The peak period starts at time  $t_o$  and ends at time  $t_f$ . The demand rate,  $h(t)$ , is equal to capacity  $\mu_I$  at times  $t_o$  and  $t_f$ , it is larger than  $\mu_I$  in time interval  $[t_o, t_f]$ , and it is less than  $\mu_I$  outside this interval. During the off-peak period there is no queue and vehicles can be served without delay. Incidents may occur at any time in the day during peak or off-peak periods. An incident is classified as a peak period incident if it occurs during time interval  $[t_o, t_f]$ , while an off-peak incident is one that occurs outside this interval. Thus, when a peak period incident occurs two bottlenecks in series are created on Route 1.

Without loss of generality we consider only incidents on Route 1, because analysis of incidents on Route 2 would be similar. An incident may occur upstream of  $E$ , downstream of  $E$ , or at bottleneck  $E$ . Depending on the time of occurrence and location of the incident, some possible incident scenarios are shown in Table 2.1. Each cell in this table represents an incident scenario. Hybrid scenarios are also possible, as illustrated by directions of the arrows, an incident may occur during the off-peak period and continues


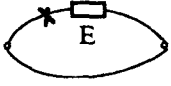




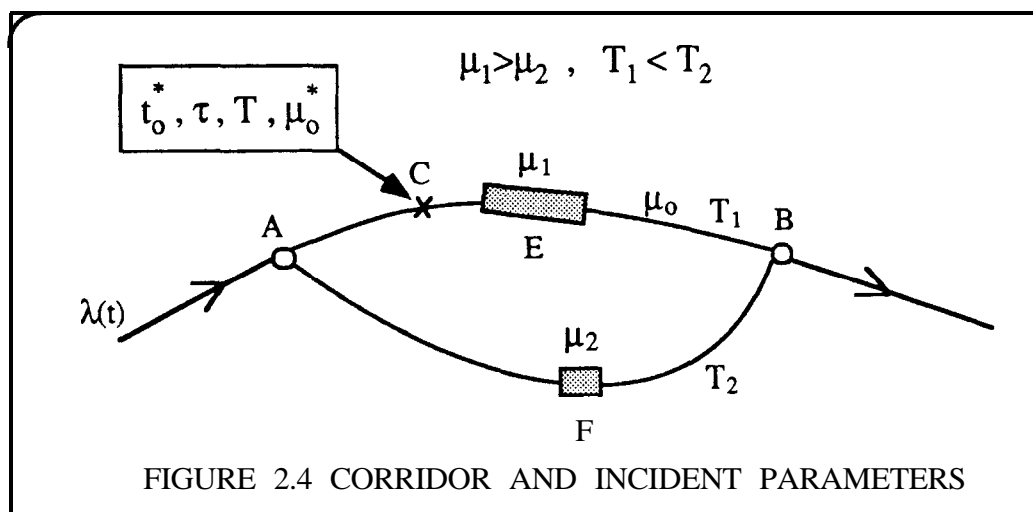
<i>LOCATION</i> on Route 1  <i>TIME</i> of day	UPSTREAM	 IN-BOTTLENECK	DOWNSTREAM
	OFF-PEAK PERIOD		
PEAK PERIOD			

TABLE 2.1 POSSIBLE INCIDENT SCENARIOS

through the peak period or vice versa. This study considers only off-peak incidents, but it will be illustrated in Chapter 5 how to apply the same approach to peak period incidents.

In all scenarios we consider the following: we assume that the location of the incident is such that there is sufficient queuing space upstream of it so that the queue does not back up into junction A. Once travellers pass point A, information from ATIS becomes irrelevant since they would be already committed to one of the two routes. ATIS information will therefore be directed at traffic as it approaches point A. The incident occurs at point C and reduces the capacity of Route 1 from  $\mu_0$  to  $\mu_0^*$ . The incident occurs at time  $t_0^*$  and lasts for a duration  $T$  as illustrated in Figure 2.4. Point C is  $\tau$  units of travel time away from A along Route 1, and  $0 < \tau < T_1$ .

To analyze the occurrence of incidents we construct deterministic queuing diagrams for this corridor. In the following paragraphs we illustrate the construction of the queuing diagram for an off-peak incident scenario.



### Construction of Queueing Diagram for an Off-Peak Incident

During the off-peak period the arrival rate at A,  $h(t)$ , is less than the bottleneck capacity,  $\mu_1$ , on the freeway. This means that  $h(t)$  is equal to the flow rate during this period. Furthermore,  $h(t)$  does not have sharp fluctuations as in the case of the peak

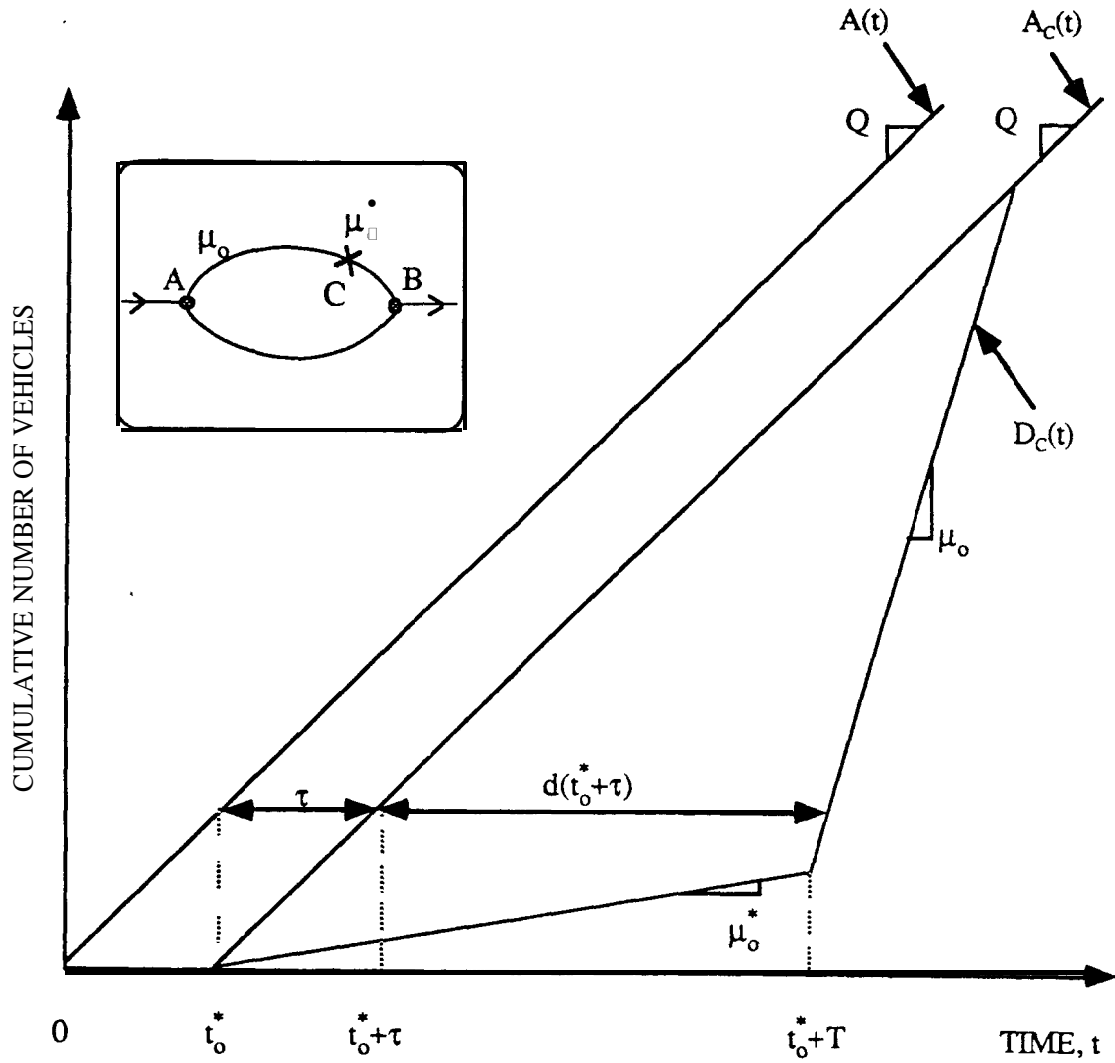
period. Hence, for simplicity,  $h(t)$  may be treated as a constant,  $Q$ , over long time intervals during the off-peak period.

Figure 2.5 illustrates the queueing diagram for an off-peak incident scenario where an incident occurs downstream of bottleneck  $E$ , and in which the incident queue starts and vanishes during off-peak conditions.

In the absence of **ATIS**, or any other information about the incident or its impact on travel times, travellers will continue to choose between routes 1 and 2 on the basis of their *non-incident* experience. As mentioned above, this means all traffic at point  $A$  will choose Route 1. As long as the back-up caused by the incident does not reach point  $A$ , the queue will evolve as shown in Figure 2.5. Traffic arrives at point  $A$  according to the arrival curve  $A(t)$ , and  $\tau$  units of time later at the incident point  $C$  according to curve  $A,(t)$ . Note that the slope of both of these curves is  $Q$ , the traffic flow rate.  $D,(t)$  shows the departure from the bottleneck. The departure flow rate is initially  $\mu_o^*$ , the reduced capacity of the bottleneck, and then after the incident is cleared at time  $T+t_o^*$ , it is the restored capacity  $\mu_o$ . The incident delay for a traveller who arrives at time  $t_o^*$  is denoted as  $d(t_o^*+\tau)$ . Note that Figure 2.5 illustrates the evolution of the queue for one of a number of possible cases. The rest of these cases will be described in Chapter 3.

## 2.5 Information Dissemination Strategy

Information about diversion to the shortest route is disseminated to travellers equipped with **ATIS** as they approach point  $A$ . Assuming that guided traffic follows the advice, then this leads to equilibrium between the two routes as defined by Wardrop (1952). Therefore, this information dissemination strategy is referred to as the user equilibrium or the user optimal strategy. When it is applied to the corridor with the incident described earlier, several cases of queue evolution results. There is a host of factors which can predict what case of queue evolution will result, most important among them is the



$$d(t_o^* + \tau) > T - \tau$$

FIGURE 2.5 QUEUE EVOLUTION FOR AN OFF-PEAK INCIDENT SCENARIO WITHOUT INFORMATION

fraction of vehicles equipped with **ATIS**. **Arrival** and departure curves are drawn and flow diversion of vehicles equipped with **ATIS** is described in each case. Once queue evolutions are determined, cases where **ATIS** is beneficial are identified, and benefits to guided and unguided travellers are evaluated. Cases of queue evolution are discussed in detail in **Chapter 3**.

There are other optimization strategies for information dissemination which can be used to influence route choice of guided traffic to achieve certain objectives. Examples of these strategies are system optimal and group optimal. The focus of this dissertation is on the application of the user optimal strategy. A brief discussion of the other strategies is provided in Chapter 5.

## **2.6 Evaluation of ATIS benefits**

In this analysis, benefits of **ATIS** are expressed as percent travel time savings. Travel time savings are referenced to travel time of a base case in which there is an incident in the absence of **ATIS** or any other type of information. Savings of other types of travel costs such as vehicle operating costs (fuel cost, cost of wear and tear) are directly related to savings in travel time.

When they are diverted to the shortest route, guided travellers suffer less or no delay in their trips, As a result of diverting guided traffic approaching the incident location, the incident queue vanishes faster and delay is also reduced for unguided traffic. Thus, diversion is expected to result an overall reduction in queueing delay in the corridor. The net reduction in queueing delay minus any increase in travel time on the **alternate** route is used as an indicator of system benefits from **ATIS**. The purpose of analyzing system benefits is to draw main conclusions related to how effective **ATIS** is in relieving incident congestion.

Since both types of traffic (guided and unguided) receive benefits from **ATIS**, a traveller may question the need to buy such equipment and/or to subscribe to an **ATIS** service. The important questions in the analysis of user benefits under incident conditions can be summarized as follows:

- When is guided traffic better off than unguided?
- How does the distribution of benefits between guided traffic and unguided traffic vary for different market penetration levels (i.e, different proportions of guided traffic)?
- How does travellers' perception of the benefits of **ATIS** change with incremental market penetration?

The purpose of analysis of the distribution of benefits is to draw conclusions and fundamental insights that are useful for marketing research of **ATIS**.

Analysis of the benefits of **ATIS** is presented in Chapter 4 for an off-peak incident scenario and a user optimal strategy. We **also** study the sensitivity of system benefits to the relevant incident and network parameters.



### 3. QUEUE EVOLUTIONS

The objective of this chapter is to analyze cases of the queue evolution for the **off-peak** incidents with and without **ATIS**. We use the idealized corridor, with the assumptions discussed in Chapter 2, as a test bed for simulation of the incidents. A user optimal strategy is implemented to disseminate real time traffic information to travellers equipped with **ATIS**. The impact of **ATIS** on the evolution of queues is **summarized** at the end of this chapter.

#### 3.1 Off-Peak Incident Scenarios

In this section we look at the three off-peak incident scenarios which are shown in the first row of Table 2.1. Possible queue evolutions of the off-peak incident scenarios are illustrated in Figures 3.1 - 3.3 (in the same order as they appear in Table 2.1, from left to right). In the first scenario, shown in Figure 3.1, incidents occur upstream of bottleneck **E** creating two bottlenecks in series on the freeway. The cumulative curves  $A(t)$ ,  $A_C(t)$ , and  $D_C(t)$  are defined as in section 2.4. Curves  $A_E(t)$  and  $DE(t)$  are the cumulative arrival and departure curves of bottleneck **E**. In order to take into account all the vehicles that are delayed by the incident, in this analysis the cumulative count arbitrarily starts  $\tau$  units of time before the incident occurs.

Although the incident occurs during off-peak conditions, a queue still forms at **E** (queueing delay is illustrated by the shaded area in Figure 3.1). This is because once the incident is cleared and the capacity of the incident section **C** is restored, the queue discharges at a rate,  $\mu_o$ , which is larger than  $\mu_I$ , the capacity at **E**. Note that the cumulative departure curve from section **C**,  $D_C(t)$ , and the cumulative arrival curve at **E**,  $A_E(t)$ , have the same shape, because we consider flow independent travel time. Similarly, if we shift  $A_E(t)$  and  $DE(t)$  to the left by a flow-independent travel time between bottlenecks **C** and **E**,  $\delta$ ,

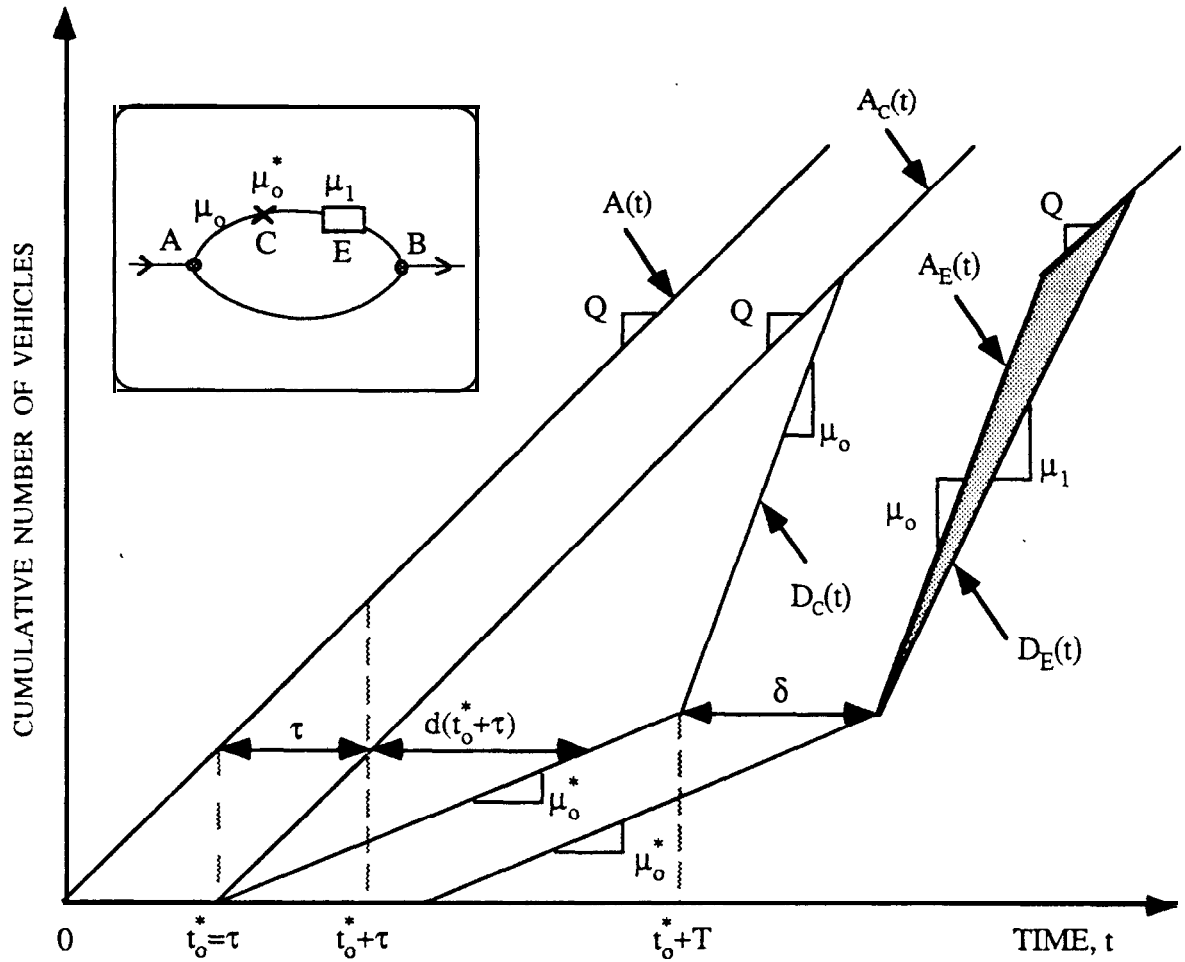


FIGURE 3.1 OFF-PEAK INCIDENT SCENARIO1  
(INCIDENT UPSTREAM OF BOTTLENECK E)

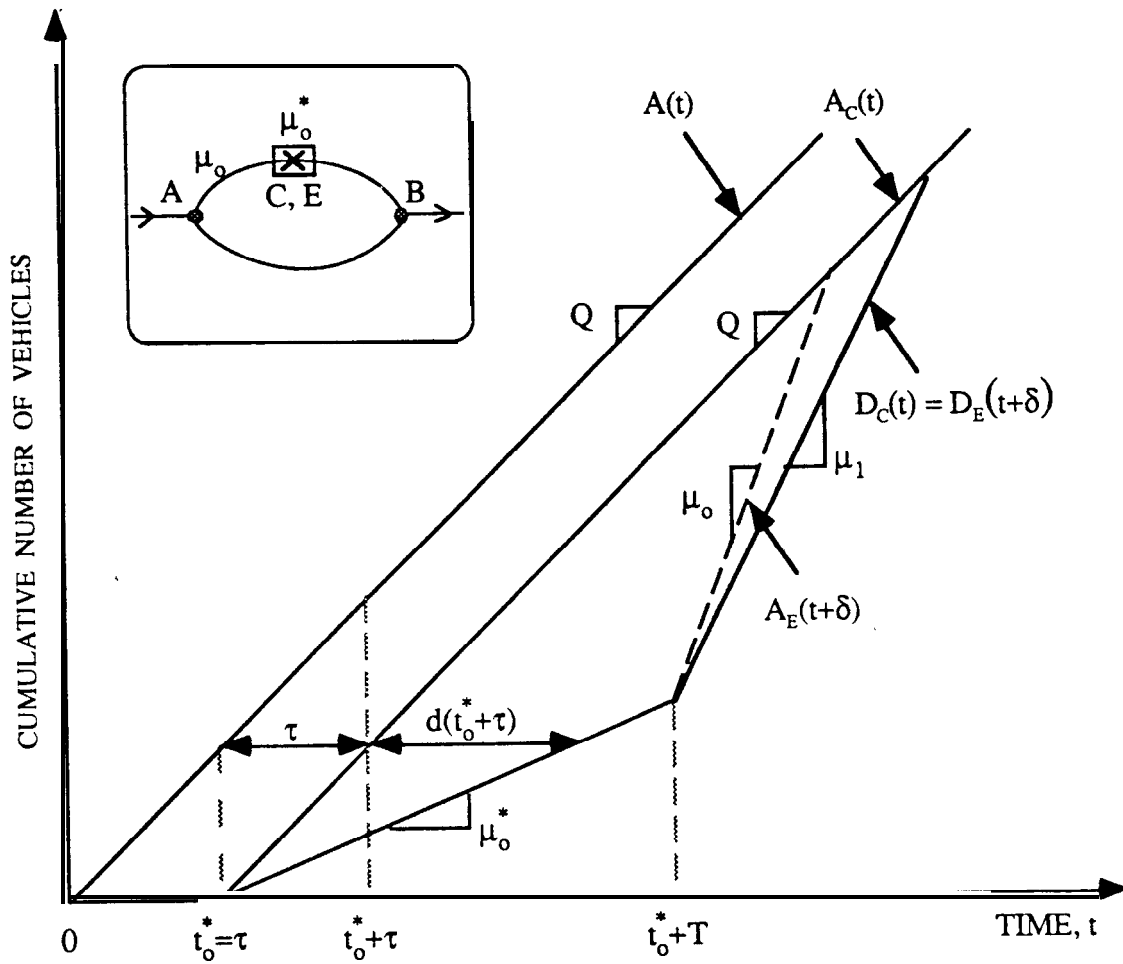


FIGURE 3.2 OFF-PEAK INCIDENT SCENARIO2  
(INCIDENT IN-BOTTLENECK E)

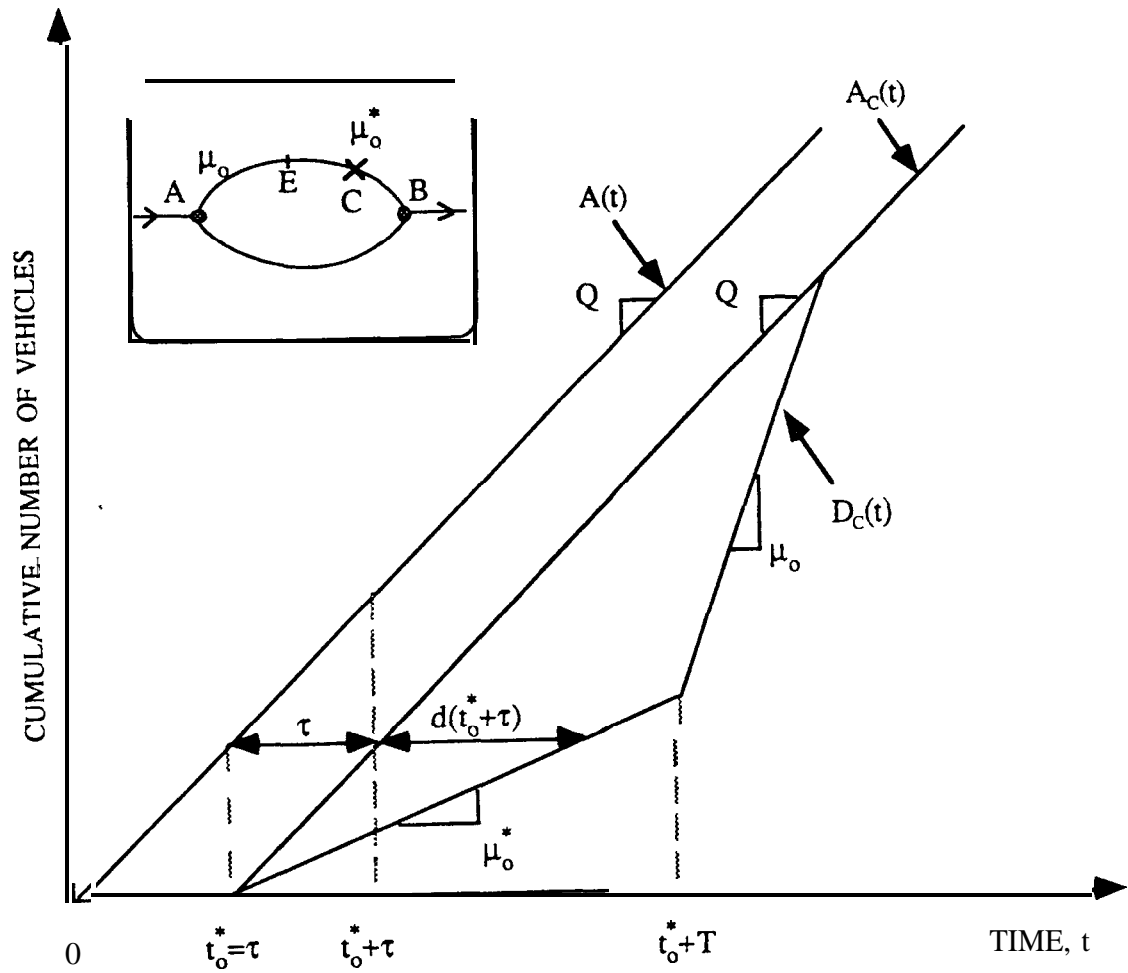


FIGURE 3.3 OFF-PEAK INCIDENT SCENARIO3  
(INCIDENT DOWNSTREAM OF BOTTLENECK E)

Figure 3.2 is obtained. Note that Figure 3.2 also shows the queue evolution for the second incident scenario, where the incident location coincides with bottleneck section E. Also note that Figures 3.2 and 3.3 are identical except that the queue discharge in one of them is larger than it is in the other ( $\mu_o > \mu_I$ ). Thus, except for the magnitude of the queue discharge, all three scenarios have identical queue evolution. Consequently, without loss of generality, we consider only one of these scenarios for analysis. We therefore choose the off-peak scenario illustrated in Figure 3.3 for the purpose of this analysis.

### 3.2 Evolution of Queues Without Information

The process for identifying cases of queue evolution without information under the off-peak incident scenario is illustrated in Figure 3.4. This figure shows that there are five possible cases. The expected incident duration,  $T$ , is an important factor in determining each. If  $T$  is less than  $(\tau Q/\mu_o^*)$ , then the queueing diagram would look as in Figure 3.5, which represents incidents with relatively short durations. The bottleneck delay,  $d(t_o^* + \tau)$ , for a traveller who arrives at  $A$  at time  $t_o^*$  (when the incident occurs) and uses the freeway to go from  $A$  to  $B$  is referred to as the “initial delay”. In Figure 3.5 the initial delay is denoted as  $d_I$ , where  $d_I$  can be derived from the geometry of Figure 3.5 as:

$$d_I = T \left( 1 - \frac{\mu_o^*}{\mu_o} \right) + \tau \left( \frac{Q}{\mu_o} - 1 \right) \quad (3-1)$$

Note that  $d_I > T - \tau$ .

If the incident duration is larger than  $(\tau Q/\mu_o^*)$ , the queueing diagram would look as in Figure 3.6, and the initial delay is denoted as  $d_{II}$ . The expression for  $d_{II}$  is derived from the geometry of Figure 3.6 as:

$$d_{II} = \tau \left( \frac{Q}{\mu_o^*} - 1 \right) \quad (3-2)$$

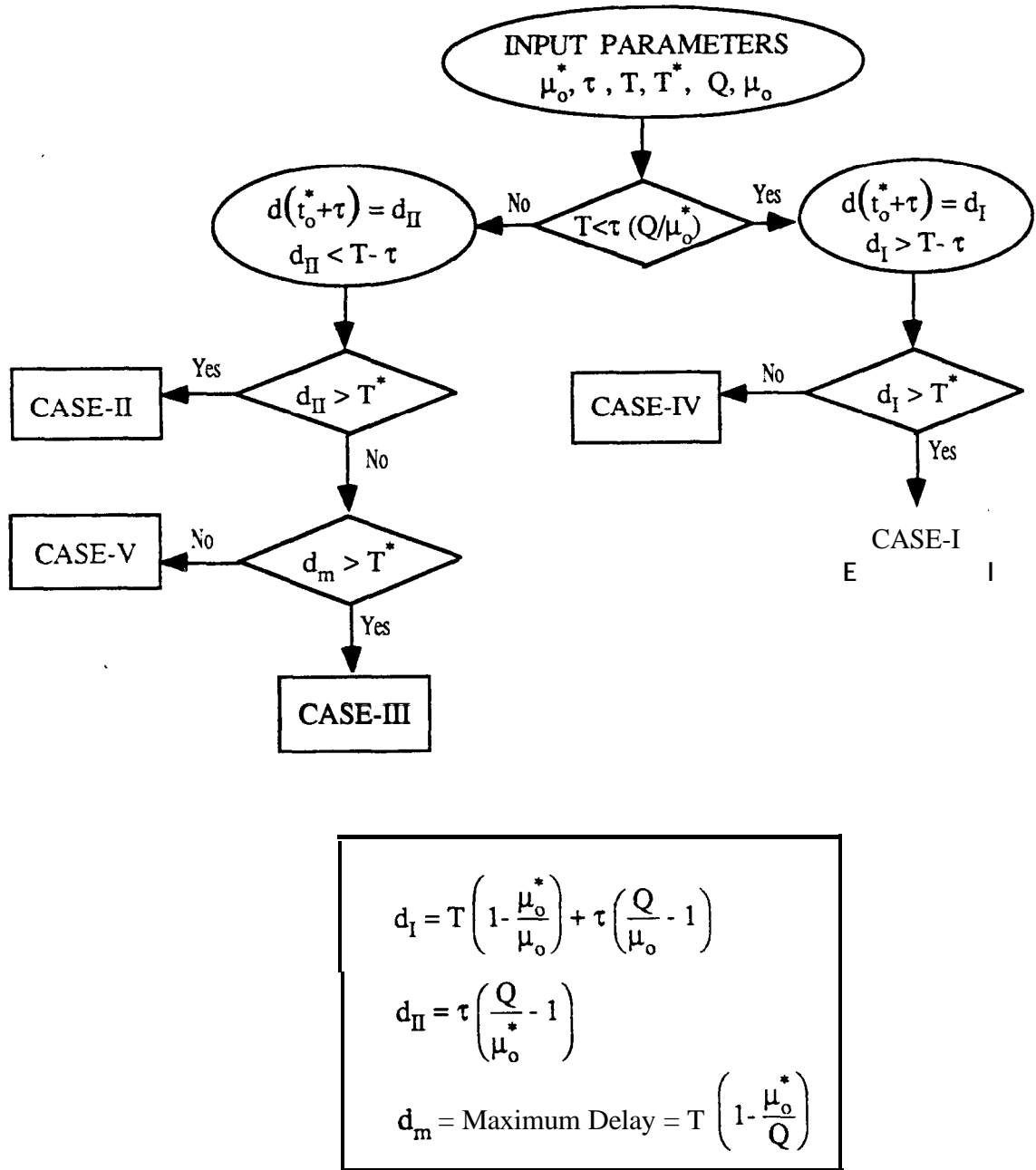


FIGURE 3.4 - CASES OF QUEUE EVOLUTION FOR AN OFF-PEAK INCIDENT SCENARIO WITHOUT INFORMATION

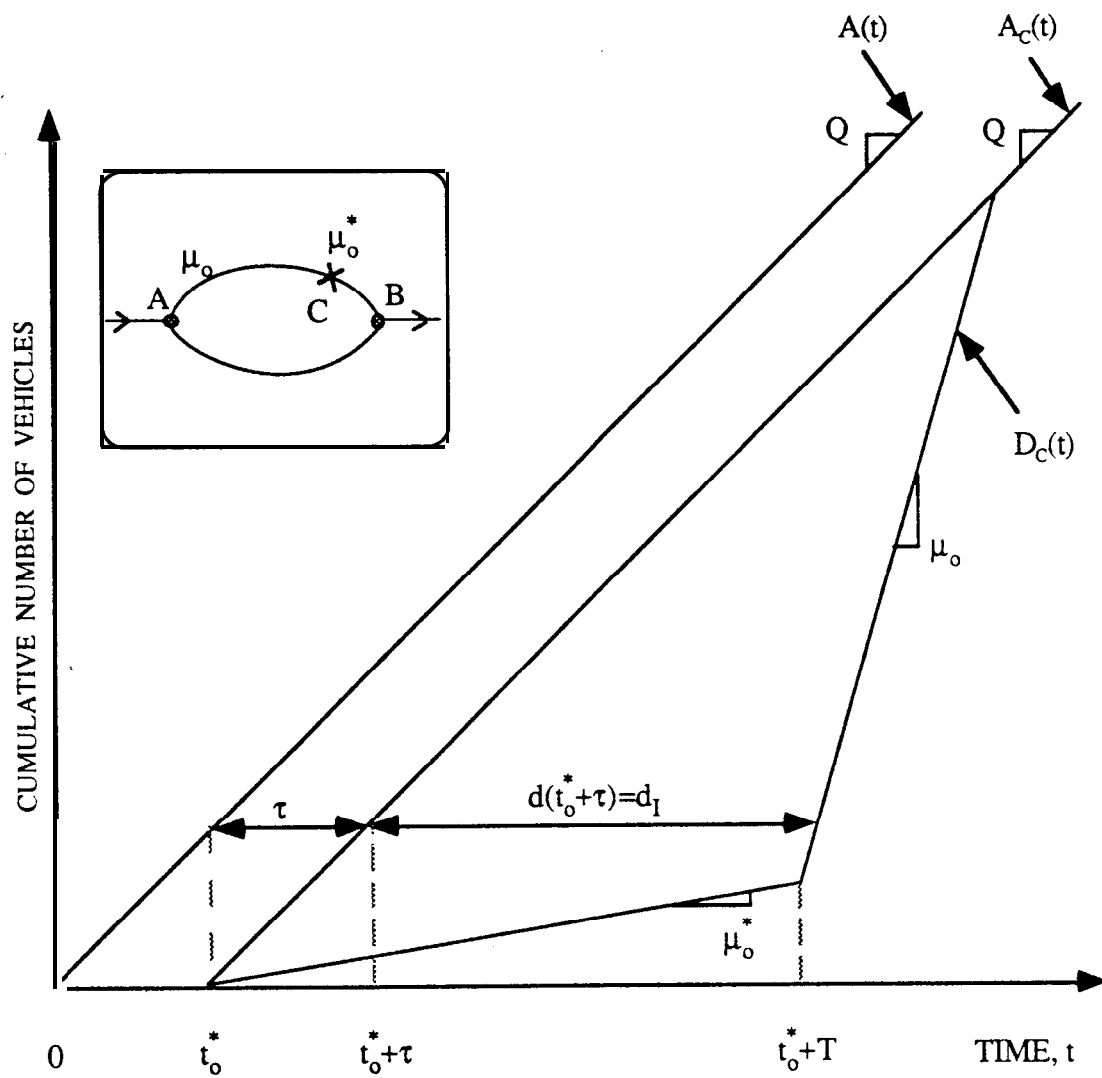


FIGURE 3.5 OFF-PEAK INCIDENT SCENARIO WITHOUT INFORMATION

$$T < \tau \left( \frac{Q}{\mu_o^*} \right) \text{ or } d_I > T - \tau$$

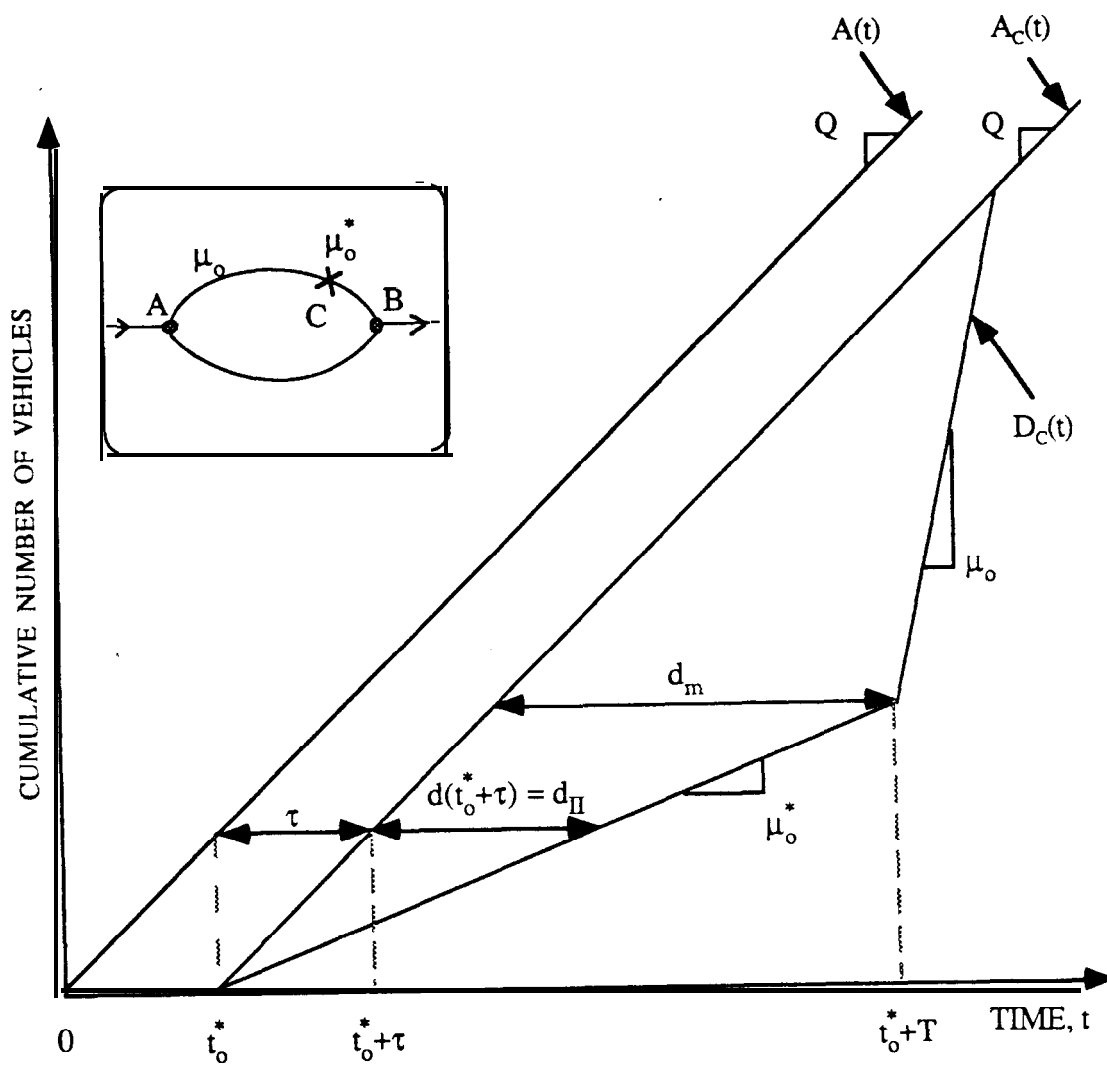


FIGURE 3.6 OFF-PEAK INCIDENT SCENARIO WITHOUT INFORMATION

$$T > \tau \left( \frac{Q}{\mu_o^*} \right) \text{ or } d_{II} < T - \tau$$



Note that  $d_{II} < T - \tau$ . Figure 3.6 represents queue evolution for incidents with relatively large durations. A brief description of each of the five possible cases is given below.

### Case I

This case is described by the following conditions

$$d_I > T - \tau,$$

and

$$d_I > T^*$$

The implication of the first condition is that a traveller who arrives at A when the incident occurs is expected to depart from C after the incident is cleared. The second condition implies that if information is available in this case, diversion can result in benefits to guided traffic.

### Case II'

This case is described by the condition

$$T^* < d_{II} < T - \tau$$

This condition implies that a traveller who arrives at A when the incident occurs is expected to depart from C while the incident is still not cleared. Note that it is also beneficial to have information in this case.

### Case III

This case is described by the following conditions

$$d_{II} < T - \tau,$$

$$d_{II} < T^*,$$

and

$$d_m > T^*$$

where  $d_m$  is the maximum possible delay and can be derived from the geometry of Figure 3.6 as:

$$d_m = T \left( 1 - \frac{\mu_o^*}{Q} \right) \quad (3-3)$$

In this case, the delay increases to an extent that information about diversion becomes beneficial.

#### Case IV

This case is described by the condition

$$T - \tau < d_I < T^*$$

It is obvious that guided travellers will not gain any benefits if they divert to the alternate route in this case because the delay never exceeds  $T^*$ .

#### Case V

This case is described by the conditions

$$d_{II} < T - \tau,$$

$$d_{II} < T^*,$$

and

$$d_m < T^*$$

Since the delay never exceeds  $T^*$ , information is also irrelevant in this case.

The conclusion is that information is relevant in three out of five possible cases: Cases I, II, and III. These cases are referred to as base cases and are used in this study to analyze the benefits from ATIS.

### 3.3 Evolution of Queues with ATIS

Application of the user optimal strategy to disseminate real time traffic information in the three base cases mentioned above results in a total of ten possible outcomes as shown in Figure 3.7. Each outcome represents a new case of queue evolution. Discussion of this application to the three base cases and description of the new outcomes are given below.

#### *case I*

If a user optimal strategy is applied to Case-I to instruct equipped traffic to divert, then there will be two possible outcomes: either 1) the fraction of equipped vehicles is large enough so that diverted traffic will cause a queue on the alternate route; or 2) there is not a sufficient number of ATIS vehicles to divert and cause a queue. Each of the two outcomes is represented by a new case of queue evolution. The cases are entitled NQ-Case-I and Q-Case-I. The prefix “NQ” is used to indicate that there is no queue on the alternate route, while the letter Q is used to indicate that there is a queue.

#### **NO-Case-I:**

Arrivals and departures in this case are illustrated in Figure 3.8.  $A_1(t)$  denotes the arrivals at A at time  $t$  of traffic using Route 1 (the freeway),  $A^*_C(t)$  denotes the arrivals at the incident bottleneck C when there is diversion to the alternate route, and  $A_2(t)$  denotes the arrivals to the alternate route. All equipped vehicles are instructed to divert to the alternate route for a period of time, K, after which the freeway reverts to being faster than the alternate route. The length of diversion period, K, is a function of  $p$ , the fraction of vehicles equipped with ATIS, with diversion expected to last longer for smaller values of  $p$ .

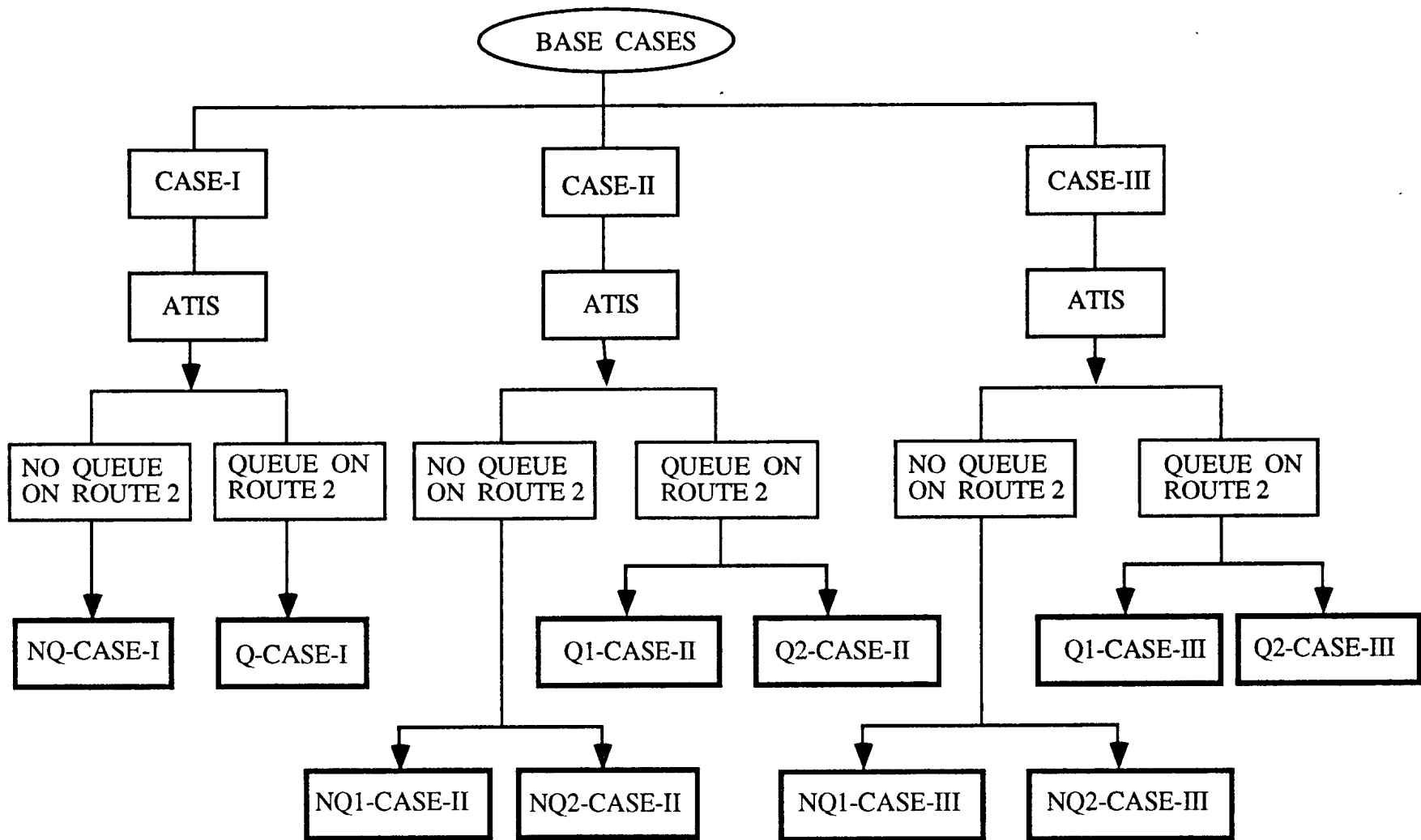


FIGURE 3.7 - APPLICATION OF USER OPTIMAL STRATEGY TO BASE CASES I, II, III

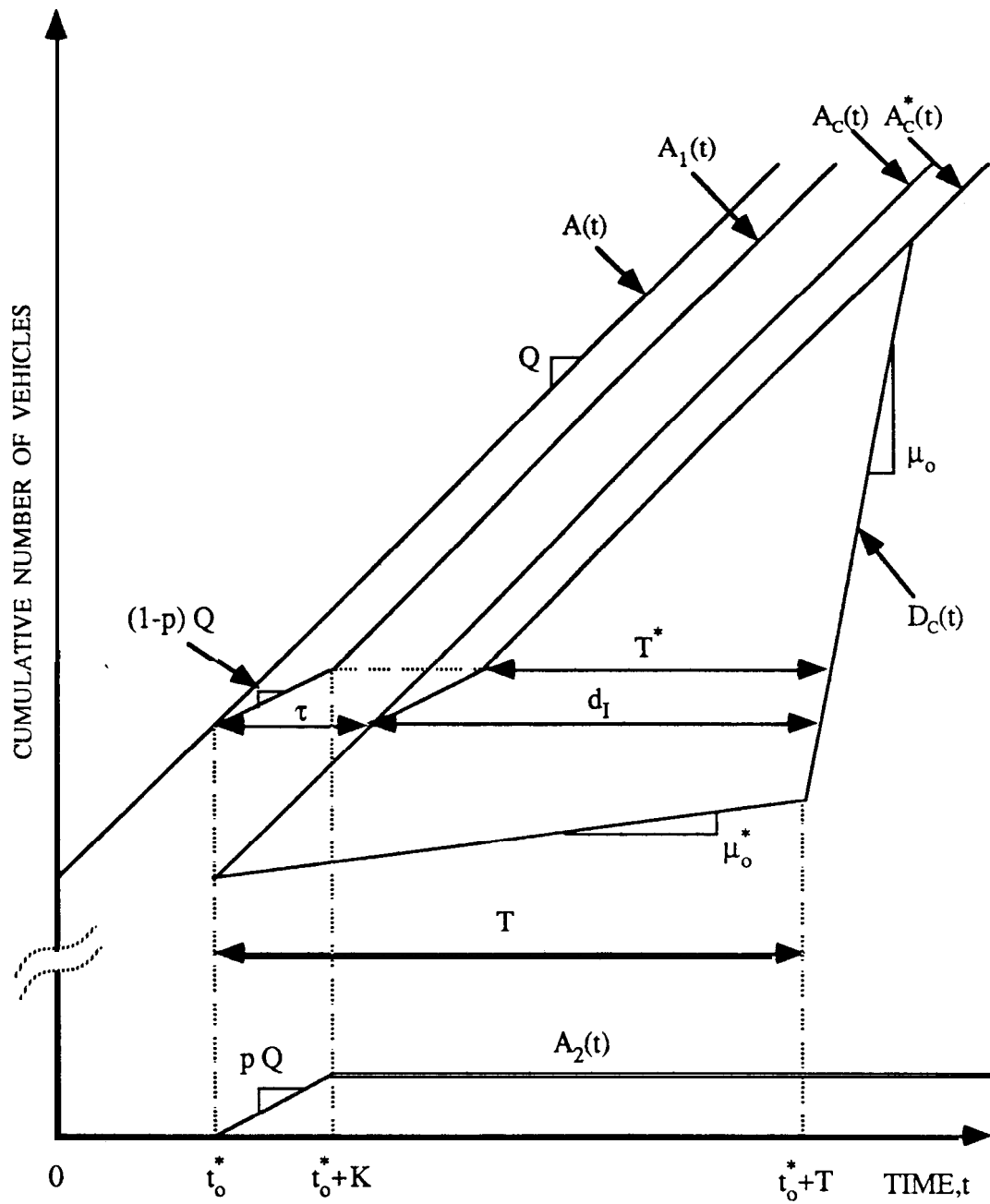


FIGURE 3.8 OFF-PEAK INCIDENT WITH ATIS (NQ-CASE-I)

$$p < (\mu_2/Q), d_I > T^*, \text{ and } d_I > T - \tau$$

O - C a s e - I :

Arrivals and departures in this case are illustrated in Figure 3.9. All equipped vehicles are diverted to the alternate route for a period of time  $K$  until equilibrium is achieved. Equilibrium lasts for a time period of  $\epsilon$  after which the freeway becomes faster and no more equipped vehicles are diverted. In order to maintain equilibrium, the diversion rate has to be decreased. The fraction  $p'$  that should be diverted to maintain equilibrium is found by solving the following simultaneous equations:

$$d_1^* = d_2^* + T^* \quad (3-4)$$

$$K + d_1^* = d_1 + \frac{(1-p) Q K}{\mu_o} \quad (3-5)$$

$$T^* + \epsilon = d_1^* + \frac{(1-p') Q \epsilon}{\mu_o} \quad (3-6)$$

$$d_2^* = K \left( \frac{p Q}{\mu_2} - 1 \right) \quad (3-7)$$

$$p' Q \epsilon = \mu_2 (\epsilon - d_2^*) \quad (3-8)$$

where  $d_1^*$  and  $d_2^*$  are delays at the start of equilibrium on routes 1 and 2 respectively. Equation (3-4) results from equilibrium conditions. Equations (3-5) and (3-6) are derived from the geometry of the cumulative curves  $A_C^*(t)$  and  $D_C(t)$  of Route 1. Similarly, equations (3-7) and (3-8) are derived from the geometry of the arrival and departure curves of Route 2.

Solving for  $p'$ ,  $K$ , and  $\epsilon$  yields:

$$p' = \frac{\mu_2}{\mu_2 + \mu_o} \quad (3-9)$$

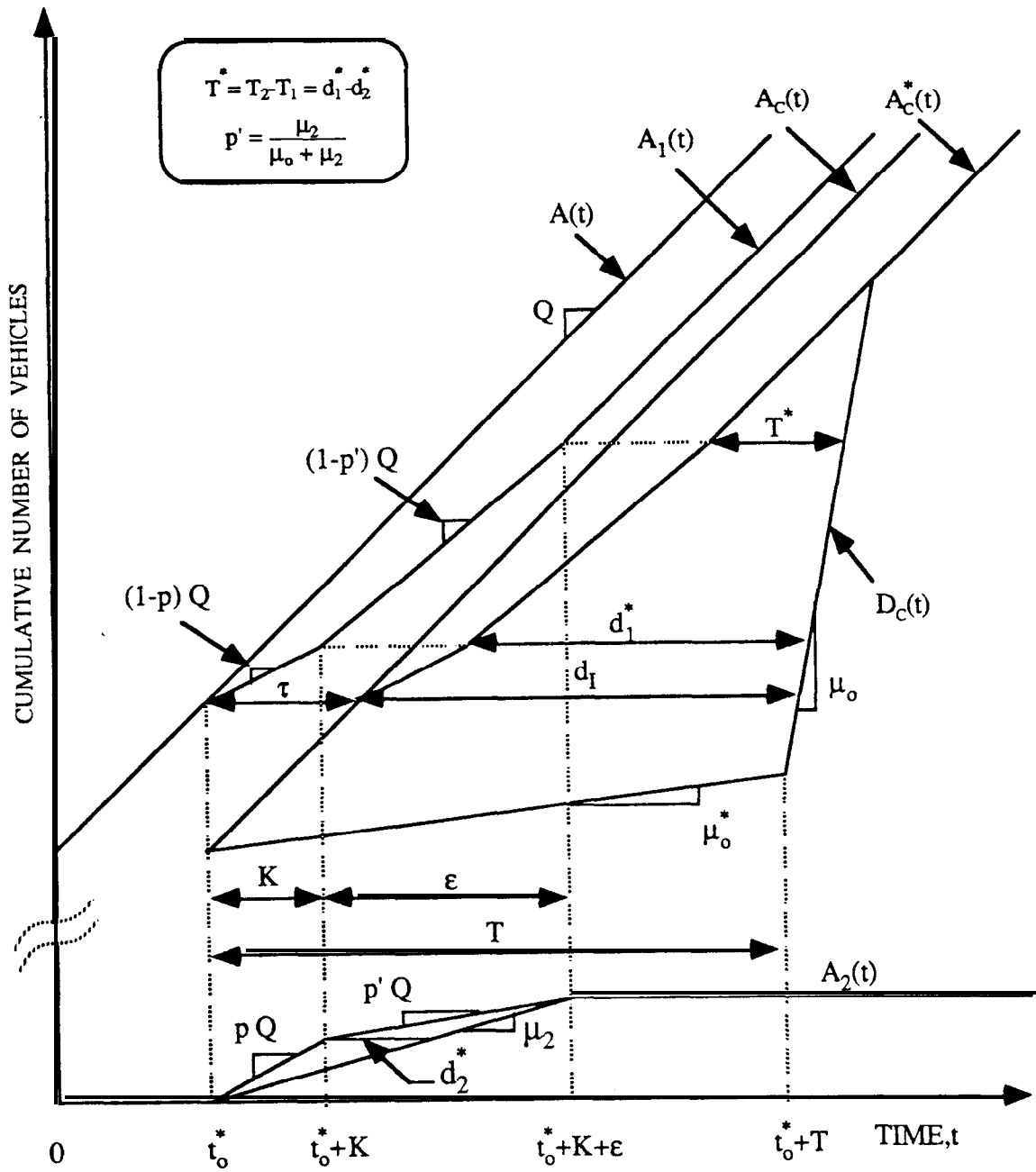


FIGURE 3.9 OFF-PEAK INCIDENT WITH ATIS (Q-CASE-I)

$$p > (\mu_2/Q), d_1 > T - \tau, \text{ and } d_1 > T^*$$

$$K = \frac{\mu_o \mu_c (d_1 - T^*)}{Q[p(\mu_o + \mu_2) - \mu_2]} \quad (3-10)$$

$$\epsilon = K \left( \frac{pQ}{\mu_2} - 1 \right) \left( \frac{\mu_o + \mu_2}{\mu_o + \mu_2 - Q} \right) \quad (3-11)$$

The expression for  $p'$  in equation (3-9) has a simple interpretation; it says that during equilibrium conditions, the demand is divided between the two routes proportional to their capacities. In fact, it can be proved that this expression is general and that it also applies to the problem when the demand on both routes is varying with timer.

Lemma 1: In order to maintain equilibrium when both the incident and the Route 2 bottlenecks are busy, the fraction of vehicles that must be diverted to Route 2 is equal to the ratio of the capacity of Route 2 to the total available corridor capacity.

Proof:

Figure 3.10 illustrates the arrivals and departures for both the incident and the Route 2 bottlenecks. The demand to be served by each bottleneck varies with time. Equilibrium between the two routes starts at time  $t_s$  and ends at time  $t_f$ , and all vehicles use Route 1 outside time interval  $[t_s, t_f]$  because it is faster.

It can be shown, from the geometry of the cumulative curves on Route 1, that at any time  $t$ ,  $t \in [t_s, t_f]$ :

$$A_1(t) = \mu_o^* T + \mu_o [w_1(t) + t - T] \quad (3-12)$$

where

$w_1(t)$ : queueing delay on Route 1 at time  $t$

Taking the first derivative with respect to  $t$  results in:

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<sup>1</sup> This expression also applies for equilibrium under recurring congestion or non-incident conditions



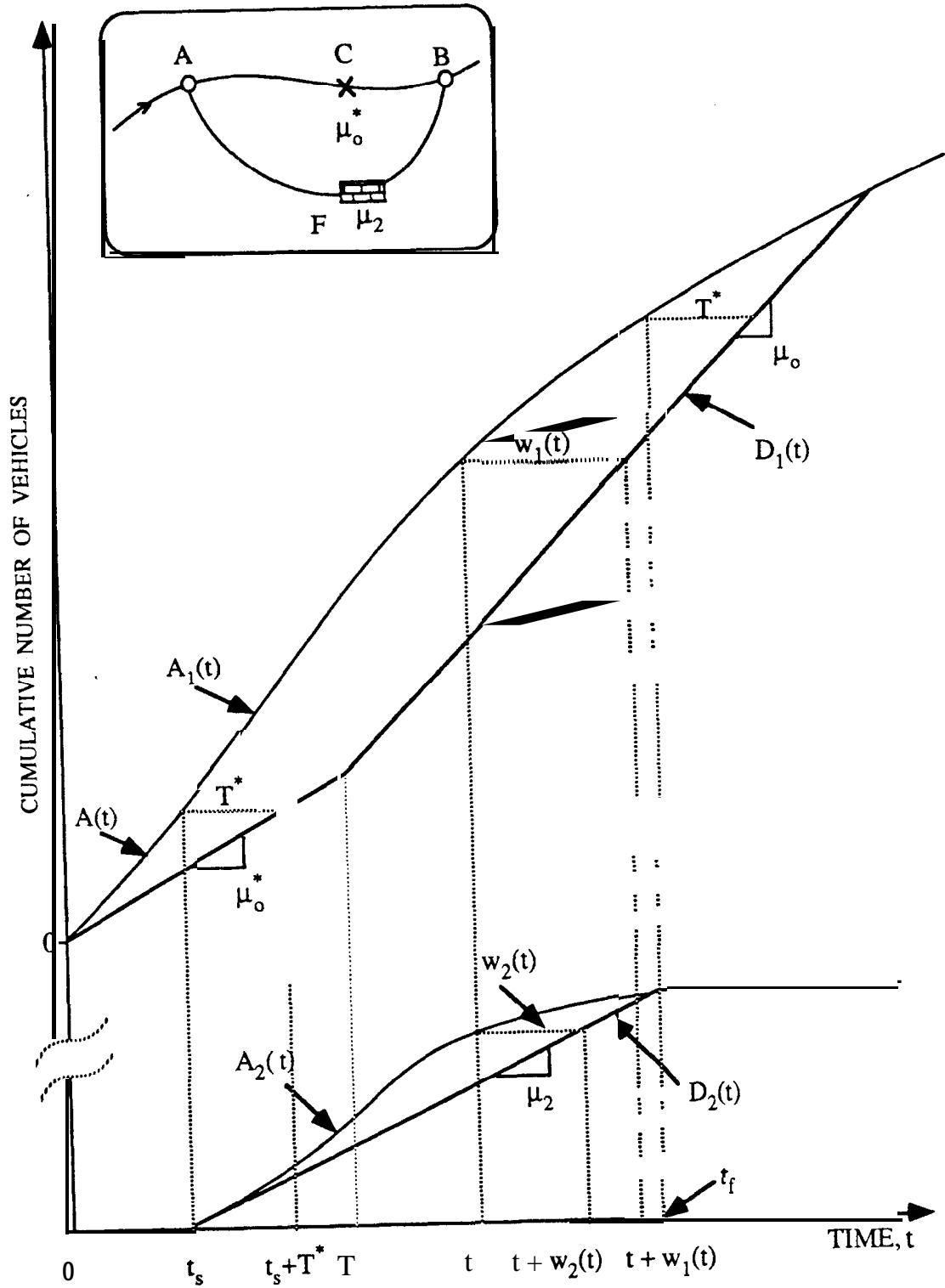


FIGURE 3.10 DERIVATION OF  $p'$

$$\frac{dA_1(t)}{dt} = \mu_o \left( \frac{dw_1(t)}{dt} + 1 \right) \quad (3-13)$$

Similarly for Route 2:

$$A_2(t) = \mu_2 (w_2(t) + t - t_s) \quad (3-14)$$

and

$$\frac{dA_2(t)}{dt} = \mu_2 \left( \frac{dw_2(t)}{dt} + 1 \right) \quad (3-15)$$

where,

$w_2(t)$ : queueing delay on Route 2 at time  $t$

At equilibrium,

$$w_1(t) = w_2(t) + T^* \quad (3-16)$$

and by taking the first derivative of (3-16) with respect to  $t$ :

$$\frac{dw_1(t)}{dt} = \frac{dw_2(t)}{dt} \quad (3-17)$$

Thus, combining equations (3-13), (3-15), and (3-17) we obtain:

$$\frac{1}{\mu_o} \frac{dA_1(t)}{dt} = \frac{1}{\mu_2} \frac{dA_2(t)}{dt} \quad (3-18)$$

which can also be expressed as:

$$\frac{dA_2(t)}{dt} = \left( \frac{\mu_2}{\mu_o} \right) \frac{dA_1(t)}{dt} \quad (3-18-a)$$

Since

$$A(t) = A_1(t) + A_2(t) \quad (3-19)$$

where,

$A(t)$ : total cumulative arrivals at point A before traffic is divided between the two routes.

Taking the first derivative of (3-19) with respect to  $t$  results in

$$\frac{dA(t)}{dt} = \frac{dA_1(t)}{dt} + \frac{dA_2(t)}{dt} \quad (3-20)$$

Substituting for  $(dA_2(t)/dt)$  as given by equation (3-18-a) into equation (3-20) results in

$$\frac{dA(t)}{dt} = \left( \frac{\mu_2 + \mu_o}{\mu_o} \right) \frac{dA_1(t)}{dt} \quad (3-21)$$

Thus,

$$\frac{dA_1(t)}{dt} = \left( \frac{\mu_o}{\mu_2 + \mu_o} \right) \frac{dA(t)}{dt} \quad (3-22)$$

and by substituting (3-22) into (3-18-a) we find that

$$\frac{dA_2(t)}{dt} = \left( \frac{\mu_2}{\mu_2 + \mu_o} \right) \frac{dA(t)}{dt} \quad (3-23)$$

Equations (3-22) and (3-23) say the following: under equilibrium conditions, the traffic demand approaching point A is divided between the two routes such that the demand on each route is proportional to its capacity. Therefore,  $p'$ , or the fraction of total demand  $(dA(t)/dt)$  that must be diverted from Route 1 to Route 2 during equilibrium is equal to the coefficient on the right side of equation (3-23), which is also given by equation (3-9). Note that,  $p'$ , the fraction of vehicles that must be diverted to maintain equilibrium once it is reached is not a function of  $p$ , the fraction of vehicles equipped with ATIS. However, if equilibrium is to be achieved, then clearly  $p$  must equal or exceed it. This implies that some equipped travellers will be selected to divert to the alternate route while others will be asked

to remain on Route 1. This is a non trivial task and requires that communication is established with individual **ATIS** vehicles as they route in the network\*.

The total time interval during which there is diversion is found by **adding** equations (3-10) and (3-11) and simplifying:

$$K + \epsilon = \frac{\mu_o (d_I - T^*)}{\mu_o + \mu_2 - Q} \quad (3-24)$$

From which we can find the total number of vehicles diverted in this incident,  $N_d$ :

$$N_d = \frac{\mu_2 \mu_o (d_I - T^*)}{\mu_o + \mu_2 - Q} \quad (3-25)$$

Note that this number is a function of the incident and the corridor parameters only and is independent of  $p$ .

## Case II

Application of the user optimal strategy to Case II results in a total of four cases of queue evolution: NQ1-Case-II, NQ2-Case-II, Q1-Case-II, and Q2-Case-II. These cases are discussed below.

### NQ1-Case-II and NQ2-Case-II

NQ1-Case-II and NQ2-Case-II are shown in Figures 3.11 and 3.12 respectively. In both cases no queue forms on Route 2 because of the low proportion of guided traffic. In NQ1-Case-II, the fraction of vehicles equipped with **ATIS** is not large enough to initiate equilibrium, therefore equilibrium will not be reached until the incident queue starts to

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<sup>2</sup> A practical strategy for diversion is suggested in Chapter 5 where **ATIS** equipped vehicles are diverted in pulses. Thus, the average rate of diversion over the equilibrium period is approximately  $p' Q$ .

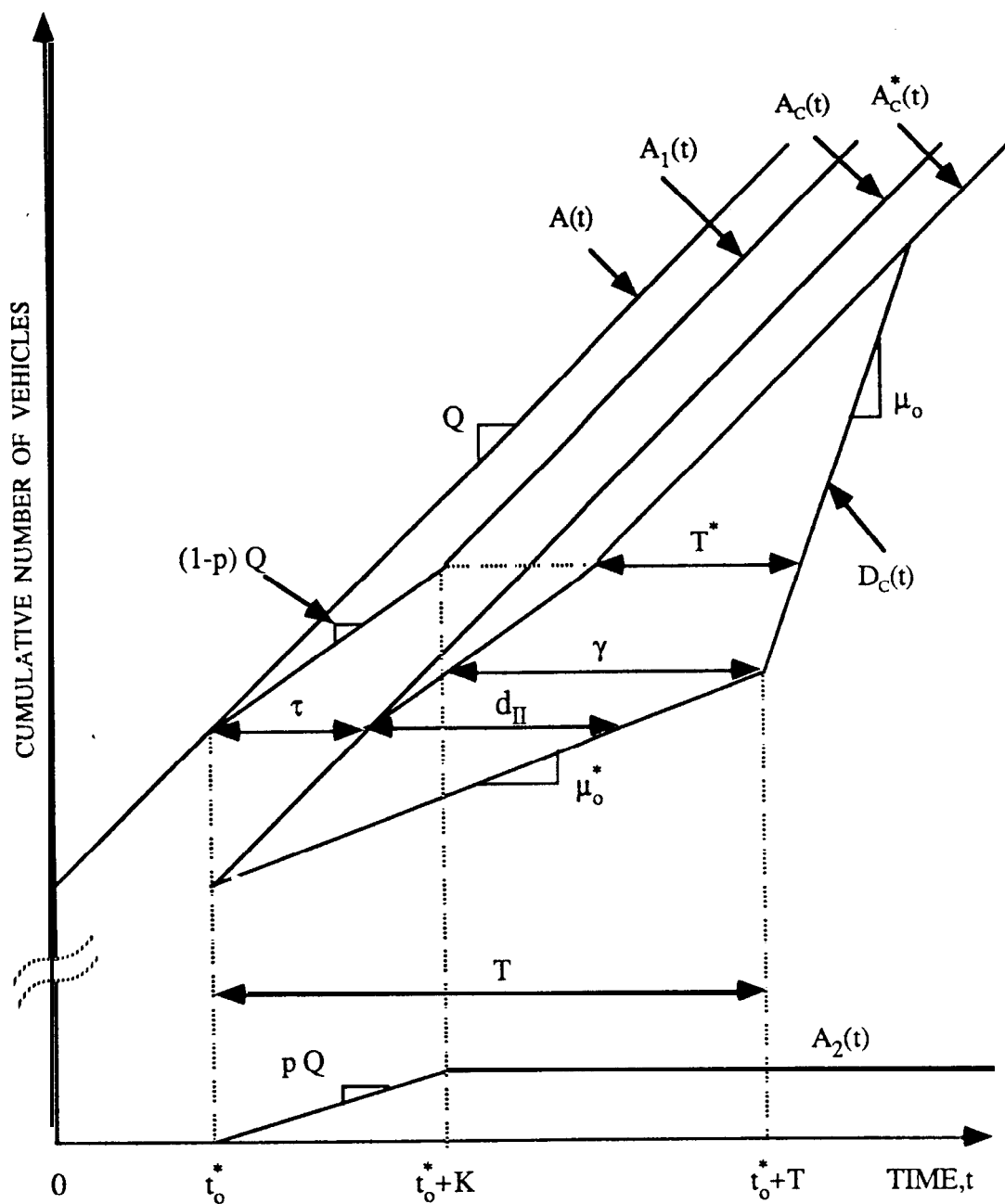


FIGURE 3.11 OFF-PEAK INCIDENT WITH ATIS (NQ1-CASE-II)

$$p < (\mu_2/Q) \text{ and } p < z'$$

$$T-z > d_{II} > T^*$$

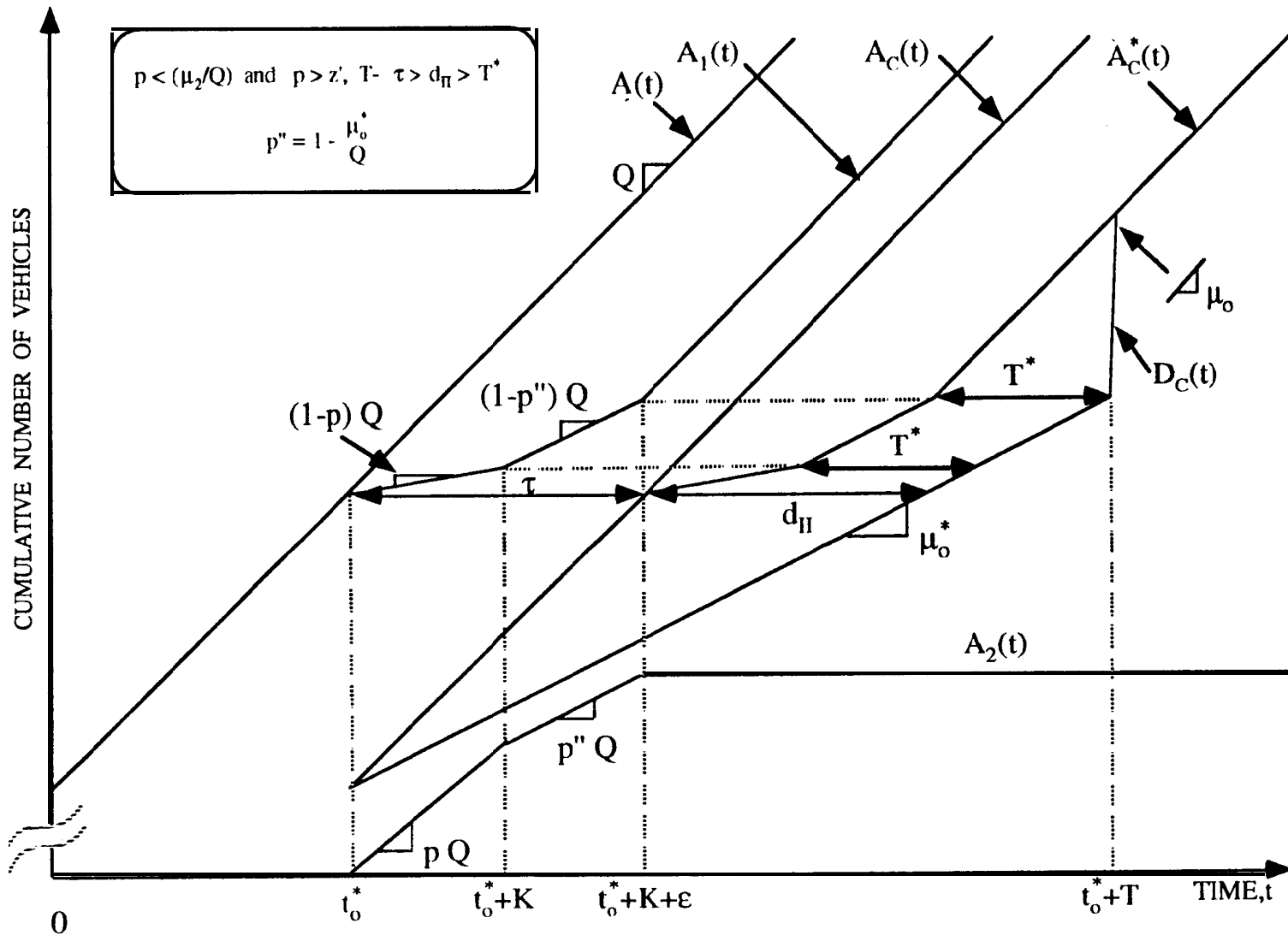


FIGURE 3.12 OFF-PEAK INCIDENT WITH ATIS (NQ2-CASE-II)

discharge. In **NQ2-Case-II**, this fraction is larger than,  $z'$ , the minimum fraction of vehicles needed to initiate equilibrium early before the incident queue starts to discharge. The expression for  $z'$  is derived **from** the geometry of the queueing diagram of **NQ1-Case-II** shown in Figure 3.11. The initial delay on Route 1,  $d_{II}$ , is larger than  $T^*$ . If the incident queue starts to discharge while equilibrium has not been reached, then the delay on Route 1 will be still larger than  $T^*$  and we continue to divert **ATIS** equipped vehicles at the maximum rate  $pQ$ . This means that:

$$\gamma > T^*$$

where

$y$  : delay on Route 1 as the incident queue begins to discharge.

A simplified expression for  $y$  can be found from the geometry of curves  $A_C^*(t)$  and  $D_C(t)$  as:

$$\gamma = T \left( 1 - \frac{\mu_o^*}{(1-p)Q} \right) + \frac{\tau p}{1-p} \quad (3-26)$$

Substituting for  $y$  in the inequality mentioned above results in:

$$p < \frac{T \left( 1 - \frac{\mu_o^*}{Q} \right) - T^*}{T - \tau - T^*} \quad (3-27)$$

The term on the right side of equation (3-27) is called  $z'$ . Thus, if  $p$  is larger than  $z'$ , then **NQ2-Case-II** results where equilibrium can be achieved earlier before the queue begins to discharge.

### Q1 -Case-II and Q2-Case-II

Q1-Case-II and Q2-Case-II are shown in Figures 3.13 and 3.14 respectively. In both cases a queue forms on Route 2, with the result that both bottlenecks become busy. The main difference between the two cases is in the magnitude of  $p$ , the fraction of vehicles equipped with ATIS. In Q1-Case-II, equilibrium is not reached until the incident queue starts to discharge. This is because the fraction  $p$  in this case is less than  $z$ , the minimum fraction needed to initiate early equilibrium, i.e., before the incident queue starts to discharge.

An expression for  $z$  is derived using Figure 3.13. Because of the insufficient number of ATIS vehicles in Q1-Case-II, the incident queue begins to discharge while the difference between the queueing delay of the two bottlenecks is larger than  $T^*$ . This means that:

$$y - \beta > T^*$$

where

$\beta$ : delay on Route 2 as the queue on Route 1 begins to discharge, and  $y$  is given by equation (3-26). An expression for  $\beta$  is derived from the geometry of the cumulative curves of routes 1 and 2. This expression is given by:

$$\beta = \left( \frac{\mu_o^* T - \tau Q}{(1-p)Q} \right) \left( \frac{pQ}{\mu_2} - 1 \right) \quad (3-28)$$

Substituting for  $y$  and  $\beta$  and simplifying results:

$$p [\mu_2 (T - \tau - T^*) + \mu_o^* T - \tau Q] < \mu_2 (T - \tau - T^*) \quad (3-29)$$

By referring to Figure 3.4 we conclude that for Case II

$$T - \tau - T^* > 0$$



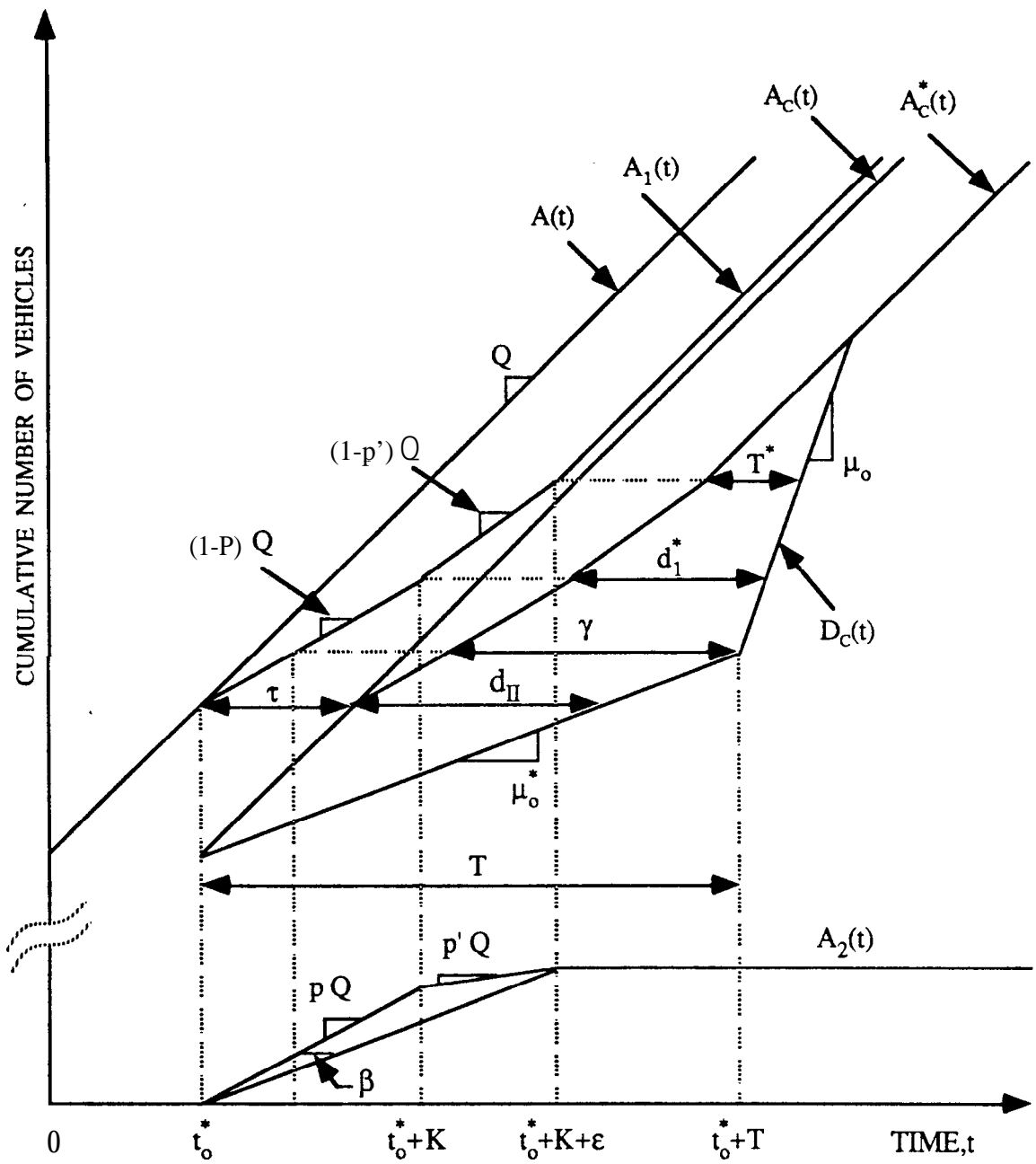


FIGURE 3.13 OFF-PEAK INCIDENT WITH ATIS (QI-CASE-II)

$$(\mu_2/Q) < p < z$$

$$T - \tau > d_{II} > T^*$$

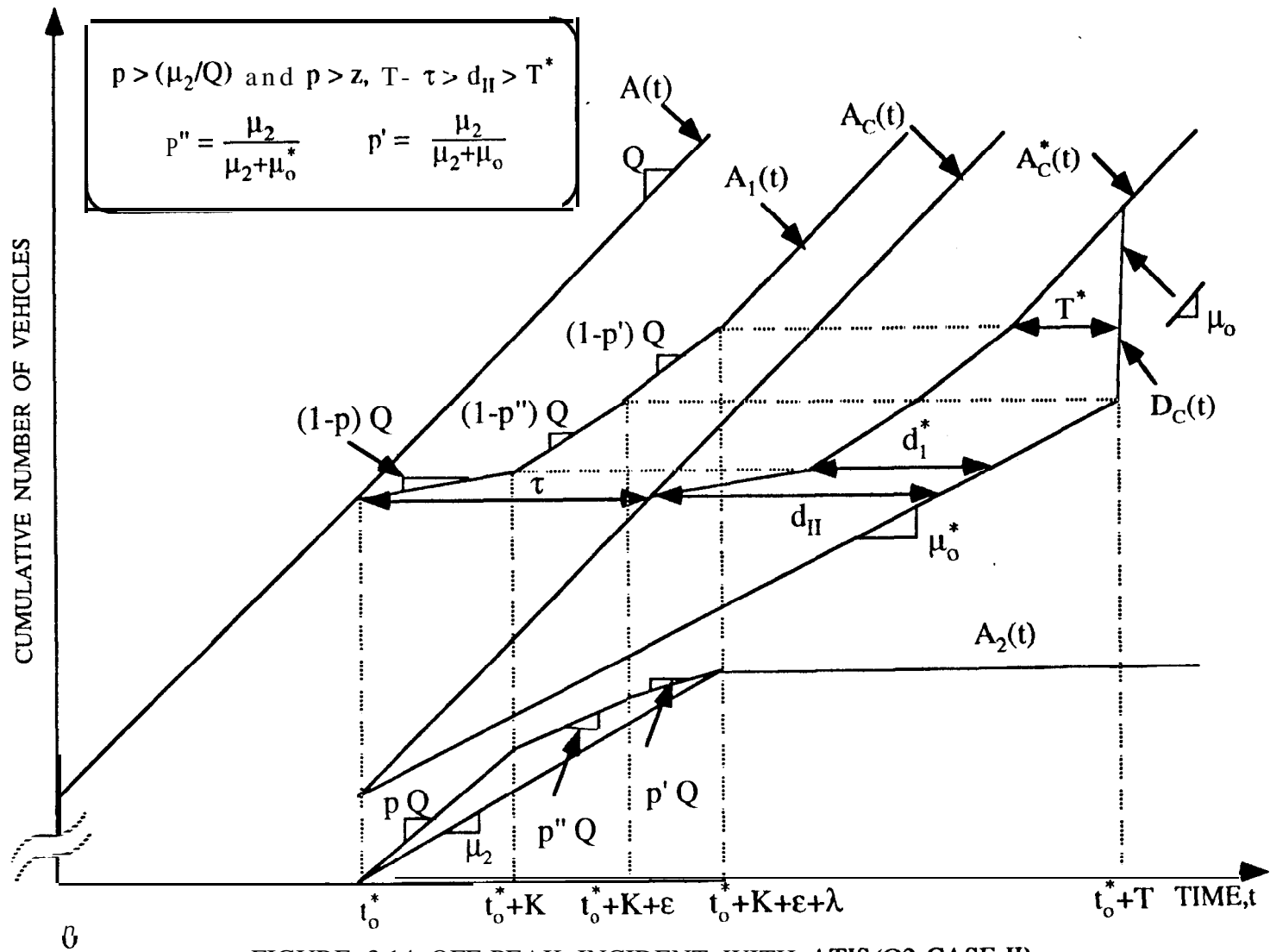


FIGURE 3.14 OFF-PEAK INCIDENT WITH ATIS(Q2-CASE-II)

and that

$$\mu_0^* T - \tau Q > 0$$

Thus, we can divide both sides of inequality (3-29) by the positive term

$$\mu_2 (T - \tau - T^*) + \mu_0^* T - \tau Q$$

to get

$$p < \frac{\mu_2 (T - \tau - T^*)}{[\mu_2 (T - \tau - T^*) + \mu_0^* T - \tau Q]} \quad (3-30)$$

Thus,  $z$  is equal to the term on the right side of this equation.

### Case III

Application of the user optimal strategy to Case-III results a total of four cases: NQ 1-Case-III, NQ2-Case-III, Q1 -Case-III, and Q2-Case-III. These cases are discussed below.

#### NO 1 -Case-III and NO2-Case-III

NQ1-Case-III and NQ2-Case-III are shown respectively in Figures 3.15 and 3.16. In both of these two cases a queue does not form on the alternate route and diversion does not start until time  $t_0^* + \alpha$ . Note that, in both cases, equilibrium is reached between the two routes at this time. In NQ1-Case-III, this equilibrium can not be maintained, however, because of the insufficient number of **ATIS** vehicles. The minimum fraction, of vehicles equipped with **ATIS**, needed to maintain equilibrium can easily be found from the geometry of the cumulative curves of NQ2-Case-III. Once equilibrium is reached while the incident queue is not discharging, equilibrium can be maintained only if

$$(1-p) Q < \mu_0^*$$

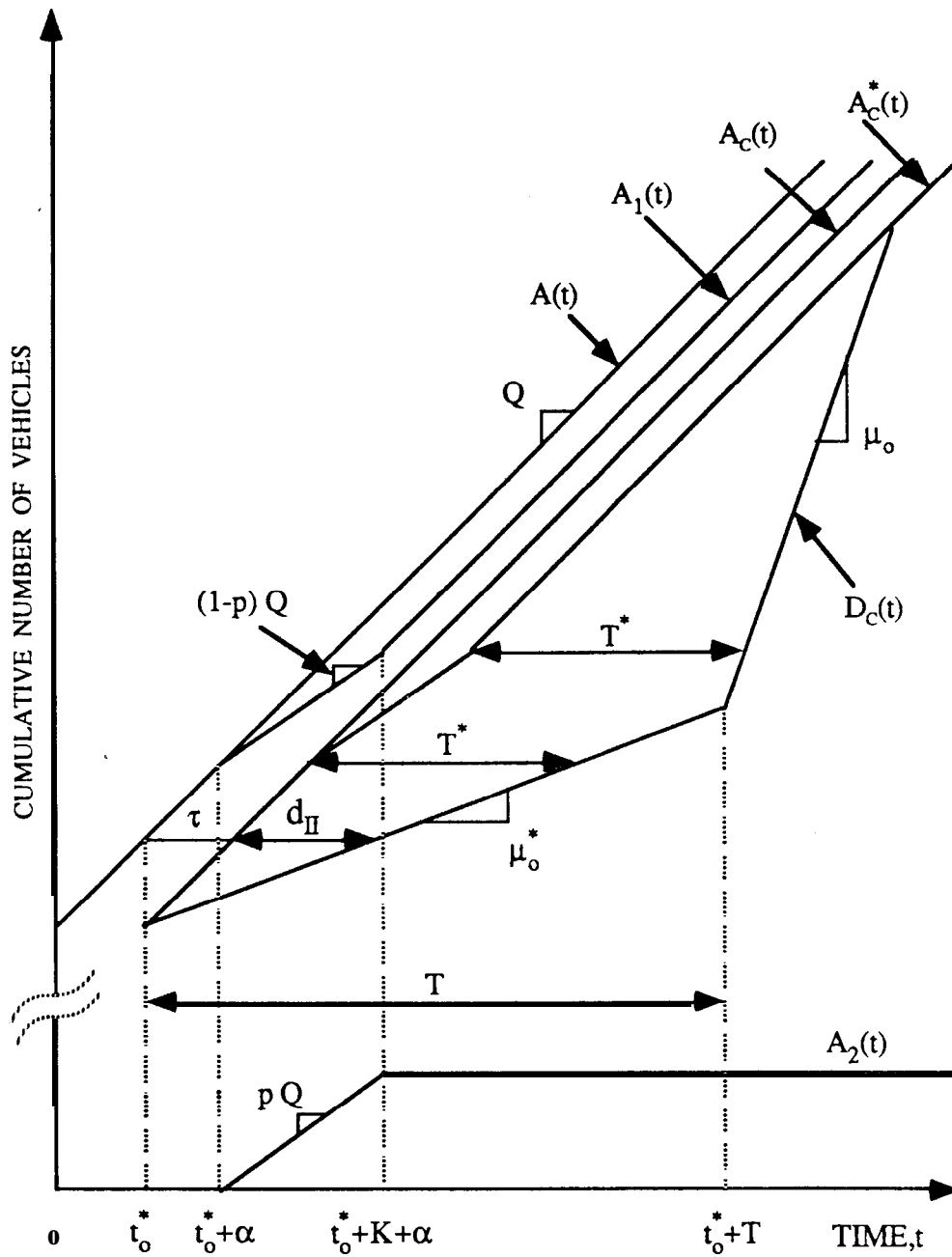


FIGURE 3.15 OFF-PEAK INCIDENT WITH ATIS (NQ1-CASE-III)

$$d_{II} < T^*, d_{II} < T - z, \text{ and } d_m > T^*$$

$$p < (\mu_2/Q) \text{ and } p < 1 - \frac{\mu_0^*}{Q}$$

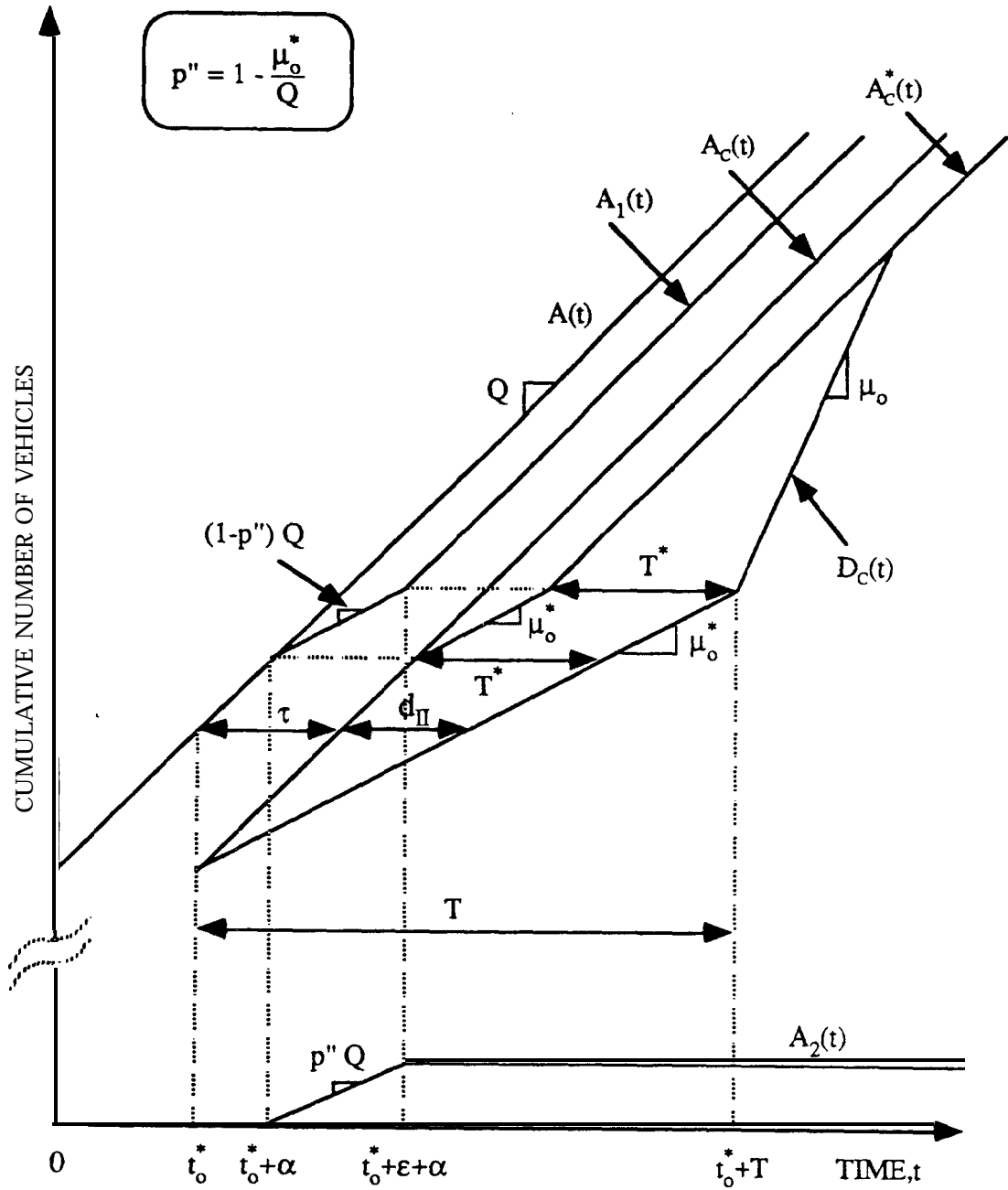


FIGURE 3.16 OFF-PEAK INCIDENT WITH ATIS (NQ2-CASE-III)

$$d_{II} < T^*, d_{II} < T - \tau, \text{ and } d_m > T^*$$

$$1 - \frac{\mu_0^*}{Q} < p < (\mu_2/Q)$$

i.e., if

$$p > 1 - \frac{\mu_0}{Q}$$

Therefore, the minimum fraction of **ATIS** vehicles needed is equal to  $1 - \mu_0^*/Q$ .

### Q1-Case-III and Q2-Case-III

Q1-Case-III and Q2-Case-III are shown in Figures 3.17 and 3.18 respectively. In both cases, the fraction  $p$  is large enough to cause a queue on Route 2. Diversion does not start until time  $t_0^* + \alpha$ . Note that delay on Route 1 keeps increasing from the start of the incident until equilibrium is achieved momentarily at time  $t_0^* + \alpha$ . In Q1-Case-III, equilibrium can not be maintained, while the incident queue is not discharging, because the proportion of guided traffic is not sufficient to maintain it. The minimum fraction  $p''$  necessary to maintain equilibrium can be determined using Lemma 1:

$$p'' = \frac{\mu_2}{\mu_2 + \mu_0}$$

### 3.4 Summary of Cases of Queue Evolution with ATIS

In summary, the application of the user optimal strategy to all cases in Figure 3.4 results in a total of twelve cases of queue evolution. The process of identifying these cases is illustrated by the flow chart shown in Figure 3.19. Information is relevant in all but two of these cases. The large number of possible cases is a result of adding another input parameter,  $p$ . In order to use this chart the following parameters need to be known:

- 1) incident parameters:  $\mu_0^*$ ,  $T$ , and  $\tau$
- 2) corridor parameters:  $\mu_0$ ,  $\mu_2$ ,  $Q$ , and  $T^*$
- 3) the fraction of **ATIS** equipped vehicles,  $p$ .

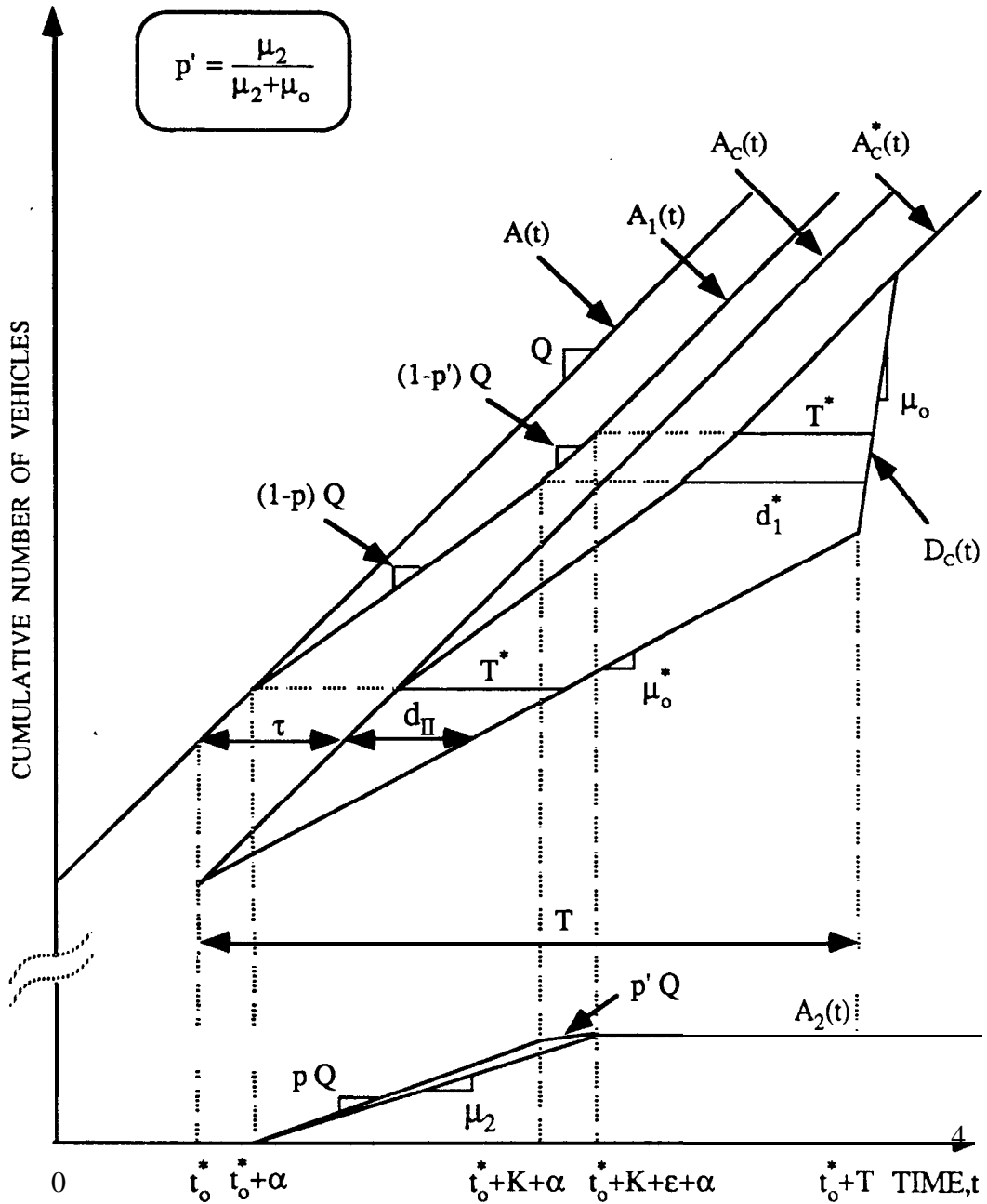


FIGURE 3.17 OFF-PEAK INCIDENT WITH ATIS(Q1-CASE-III)

$$d_{II} < T^*, d_{II} < T - \tau, \text{ and } d_m > T^*$$

$$(\mu_2/Q) < p < \frac{\mu_2}{\mu_2 + \mu_0^*}$$

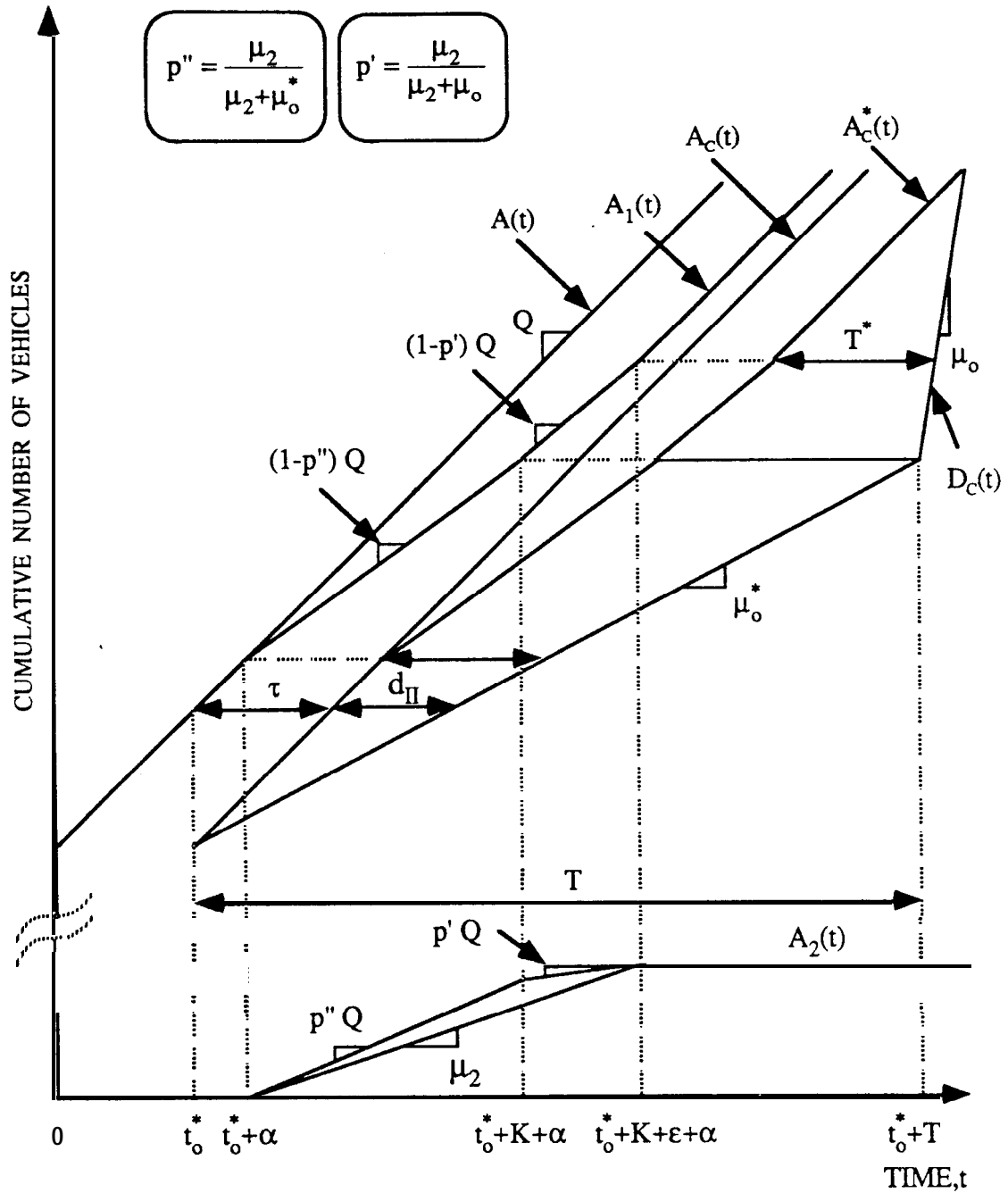


FIGURE 3.18 OFF-PEAK INCIDENT WITH ATIS (Q2-CASE-III)

$$d_{II} < T^*, d_{II} < T - \tau, \text{ and } d_m > T^*$$

$$p > (\mu_2/Q) \text{ and } p > \frac{\mu_2}{\mu_2 + \mu_o^*}$$



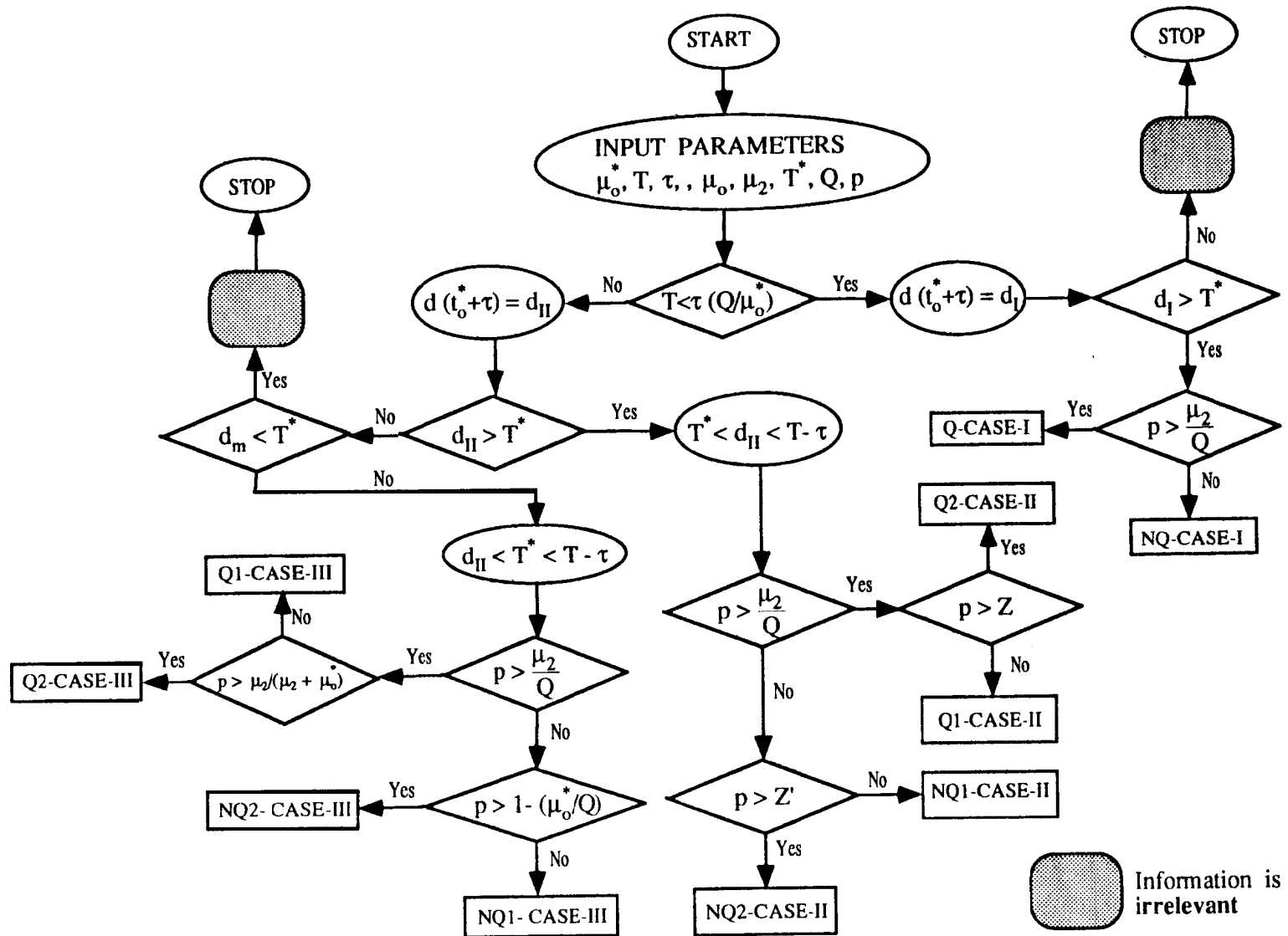


FIGURE 3.19 CASES OF THE USER OPTIMAL STRATEGY FOR AN OFF-PEAK INCIDENT WITH ATIS

If the values of these eight parameters are known, then it is straightforward to figure out which case of queue evolution will result; to determine whether **ATIS** is beneficial or not; and to use the correct queue evolution for the evaluation of **ATIS** benefits.

There is a simple procedure that describes the queue evolution in all cases:

### Rule 1

When the initial delay  $d(t_0^* + \tau) > T^*$ , guided traffic will be diverted to Route 2 at rate  $pQ$  until the difference in queueing delay between the two routes is equal to  $T^*$ . Eventually delay on Route 1 will decrease while delay on Route 2 will increase until at some point in time the difference becomes equal to  $T^*$ . This rule applies to NQ-Case-I, NQ1-Case-II, NQ2-Case-II, Q-Case-I, Q1-Case-II, and Q2-Case-II.

### Rule 2

As long as  $d(t_0^* + \tau) < T^*$  guided traffic will not be diverted to Route 2 until the delay on Route 1 becomes equal to  $T^*$ , if it ever does; it eventually does in NQ1-Case-III, NQ2-Case-III, Q1-Case-III, and Q2-Case-III; it never does in the cases IV and V for which information is irrelevant.

### Rule

This rule is a direct application of Lemma 1, and applies only when the two bottlenecks are busy. If the difference in queueing delay on the two routes equals  $T^*$  while the incident queue is discharging, then guided traffic is diverted to Route 2 at a rate  $p'Q$ , where  $p' = \mu_2/(\mu_2 + \mu_0)$ . This applies to all cases with names that start with the letter Q, i.e., Q-Case-I, Q1-Case-II, Q1-Case-III, Q2-Case-II, and Q2-Case-III. However, if the difference in queueing delay on the two routes equals  $T^*$  while the queue is still not discharging, then equilibrium can be maintained only if there is a sufficient number of

ATIS vehicles to be diverted. The diversion rate will be  $p''Q$ , where  $p'' = \mu_2/(\mu_2 + \mu_0^*)$ . This applies to Q1-Case-II and Q2-Case-III. If the number of ATIS vehicles is not sufficient to maintain equilibrium, ATIS vehicles will be diverted at the maximum possible rate,  $pQ$ . This continues until sometime after the incident queue starts to discharge, after which the diversion rate is changed to  $p'Q$ , where  $p'$  is given as above. This applies to Q1-Case-II and Q1-Case-III.

#### Rule

If a queue does not form on Route 2 and the queueing delay on Route 1 equals  $T^*$  while the incident queue is not discharging, then equilibrium can be maintained only if there is a sufficient number of ATIS vehicles to be diverted. ATIS vehicles will be diverted at rate  $Q - \mu_0^*$ . This applies to NQ2-Case-III. If the number of ATIS vehicles is not sufficient to keep equilibrium, the rate of diversion is the maximum possible,  $pQ$ , until the delay on Route 1 equals  $T^*$ . This applies to NQ1-Case-II and NQ1-Case-III.

#### Rule

Diversion to Route 2 will end only when the delay on Route 1 reaches  $T^*$  and the incident queue is discharging. This rule applies to all cases whenever information is relevant.

The implication of all this on the assessment of ATIS benefits is discussed in the following chapter.

## 4. ANALYSIS OF ATIS BENEFITS

In this chapter we analyze the benefits of **ATIS** to guided and unguided traffic as well as to the system as a whole. The analysis of benefits is based on the queueing analysis of Chapter 3. Using numerical examples, we study the sensitivity of benefits to important variables including incident and corridor parameters and the level of market penetration of **ATIS** vehicles.

### 4.1 Evaluation of User Benefits

Highway users, both guided and unguided with **ATIS**, are expected to receive benefits from the diversion of **ATIS** vehicles under incident conditions. This section demonstrates how the user benefits of **ATIS** are evaluated for a certain level of market penetration,  $p$ . The benefits are expressed as a percent travel time savings. Travel time from  $A$  to  $B$  under incident conditions and in the absence of **ATIS** is the basis for the calculations of travel time savings. In Chapter 3, it was concluded that there are only three base cases of queue evolution which can be considered for the evaluation of **ATIS** benefits: Case I, Case II, and Case III.

The benefits are evaluated by comparing the queue evolution in each base case where there is no **ATIS** with the queue evolution when **ATIS** is present. Since the user benefits depend upon the arrival time to the link where the incident occurs, the user benefits are evaluated as a function of the time of arrival at point  $A$ , the junction of the two routes. Next, we illustrate the analytic procedure used to evaluate these benefits and the results of the analysis.

### User Benefits

The analysis procedure is illustrated using Q-Case-I. The queue evolution in this case is reproduced in Figure 4.1 with the dashed lines representing arrivals and departures at points A and C under incident conditions and in the absence of ATIS. The queuing delays at time  $t$  are derived from the geometry of the arrival and departure curves of the two bottlenecks and are given as follows:

$$w_1(t) = t \left( \frac{Q}{\mu_o} - 1 \right) + T \left( 1 - \frac{\mu_o^*}{\mu_o} \right), \quad t_o^* < t < t_f \quad (4-1)$$

$$w_1^i(t) = \begin{cases} t \left[ \frac{(1-p)Q}{\mu_o} - 1 \right] + T \left( 1 - \frac{\mu_o^*}{\mu_o} \right) + \frac{\tau p Q}{\mu_o}, & t_o^* < t < t_o^* + K \\ t \left[ \frac{Q}{\mu_o + \mu_2} - 1 \right] - \tau \left( \frac{Q}{\mu_o + \mu_2} - 1 \right) \\ + K Q \left( \frac{p}{\mu_2} - \frac{1}{\mu_o + \mu_2} \right) + T^*, & t_o^* + K < t < t_o^* + K + \epsilon \\ t \left( \frac{Q}{\mu_o} - 1 \right) - (\tau + K + \epsilon) \left( \frac{Q}{\mu_o} - 1 \right) + T^*, & t_o^* + K + \epsilon < t < t_m \\ 0, & t_m < t < t_f \end{cases} \quad (4-2)$$

and,

$$w_2^i(t) = \begin{cases} t \left( \frac{pQ}{\mu_2} - 1 \right) - \tau \left( \frac{pQ}{\mu_2} - 1 \right), & t_o^* < t < t_o^* + K \\ t \left[ \frac{Q}{\mu_o + \mu_2} - 1 \right] - \tau \left( \frac{Q}{\mu_o + \mu_2} - 1 \right) \\ + K Q \left( \frac{p}{\mu_2} - \frac{1}{\mu_o + \mu_2} \right), & t_o^* + K < t < t_o^* + K + \epsilon \\ 0, & t_o^* + K + \epsilon < t < t_f \end{cases} \quad (4-3)$$

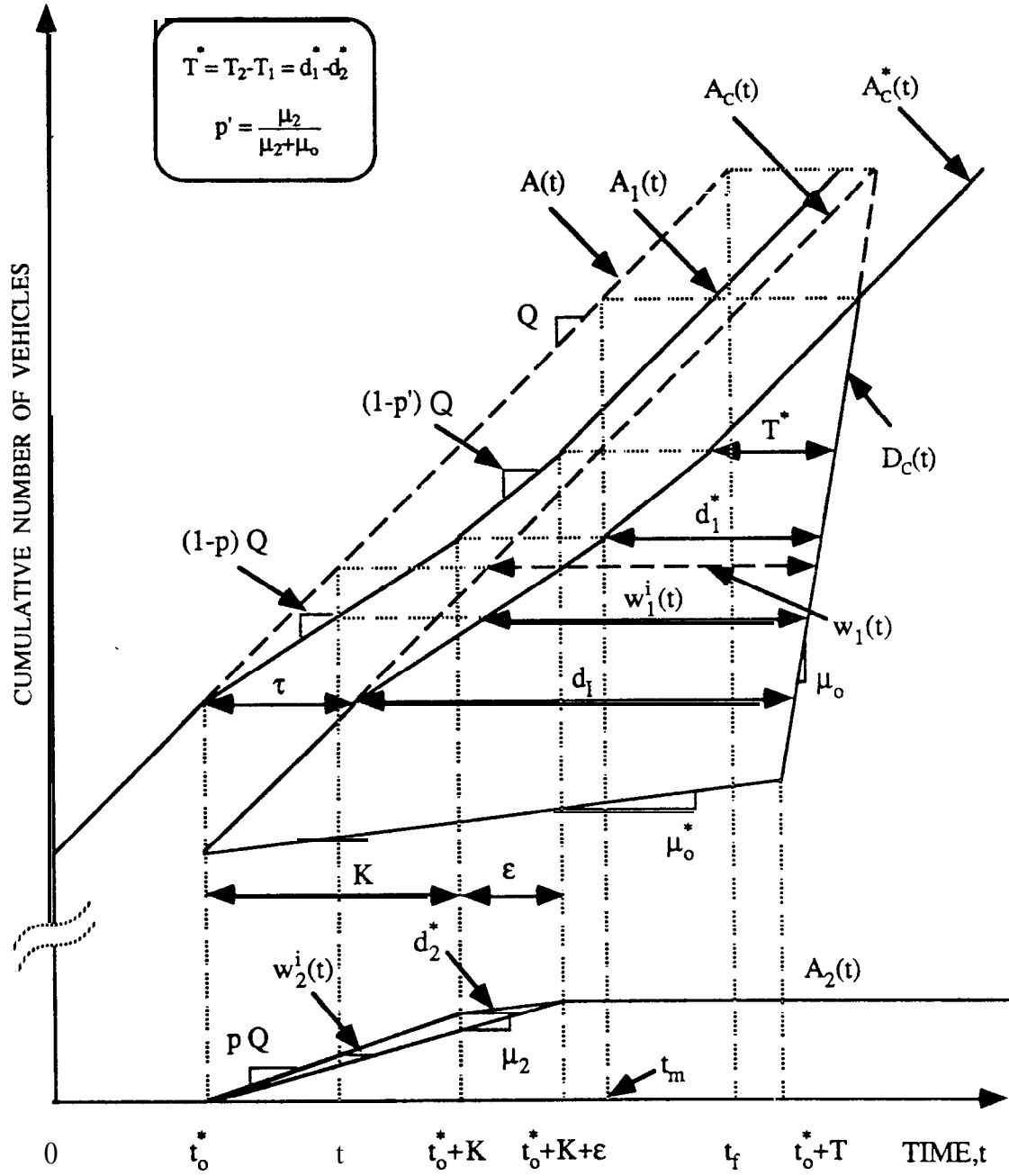


FIGURE 4.1 EVALUATION OF ATIS USER BENEFITS (Q-CASE-I)

where,

$w_1(t)$  : queueing delay on Route 1 without ATIS

$w_1^i(t)$  : queueing delay on Route 1 with ATIS

$w_2^i(t)$  : queueing delay on Route 2 with ATIS

$t_f$  : time of arrival at A for which there will be no queueing delay at C  
(without ATIS)

K and  $\epsilon$  are given by equations (3-10) and (3-11) respectively.

Hence,

$$s_d(t) = w_1(t) - w_2^i(t) - T^*, \quad t_o^* < t < t_o^* + K + \epsilon \quad (4-4)$$

and,

$$s_u(t) = w_1(t) - w_1^i(t), \quad t_o^* < t < t_f \quad (4-5)$$

where,

$s_d(t)$  : travel time savings by a traveller who arrives and is diverted at time  $t$

$s_u(t)$  : travel time savings by an undiverted traveller who arrives at time  $t$ .

It should be emphasized that all ATIS vehicles are diverted during time interval  $(t_o^*, t_o^* + K)$ , while only some of the ATIS vehicles are diverted during equilibrium time interval  $(t_o^* + K, t_o^* + K + \epsilon)$ .

Substituting for  $w_1(t)$ ,  $w_1^i(t)$ , and  $w_2^i(t)$  into equations (4-4) and (4-5) results in the expanded forms of  $s_d(t)$  and  $s_u(t)$  given by:

$$s_d(t) = \begin{cases} t Q \left[ \frac{1}{\mu_o} - \frac{p}{\mu_2} \right] + T \left( 1 - \frac{\mu_o^*}{\mu_o} \right) + \tau \left( \frac{p Q}{\mu_2} - 1 \right) - T^*, & t_o^* < t < t_o^* + K \\ t Q \left[ \frac{\mu_2}{\mu_o(\mu_o + \mu_2)} \right] + T \left( 1 - \frac{\mu_o^*}{\mu_o} \right) + \tau \left( \frac{Q}{\mu_o + \mu_2} - 1 \right) & \\ - K Q \left( \frac{p}{\mu_2} - \frac{1}{\mu_o + \mu_2} \right) - T^*, & t_o^* + K < t < t_o^* + K + \epsilon \end{cases} \quad (4-6)$$

and

$$s_u(t) = \begin{cases} t \left( \frac{pQ}{\mu_o} \right) - \frac{\tau pQ}{\mu_o}, & t_o^* < t < t_o^* + K \\ tQ \left[ \frac{\mu_2}{\mu_o(\mu_o + \mu_2)} \right] + T \left( 1 - \frac{\mu_o^*}{\mu_o} \right) + \tau \left( \frac{Q}{\mu_o + \mu_2} - 1 \right) \\ - KQ \left( \frac{p}{\mu_2} - \frac{1}{\mu_o + \mu_2} \right) - T^*, & t_o^* + K < t < t_o^* + K + \epsilon \\ T \left( 1 - \frac{\mu_o^*}{\mu_o} \right) + (\tau + K + \epsilon) \left( \frac{Q}{\mu_o} - 1 \right) - T^*, & t_o^* + K + \epsilon < t < t_m \\ t \left( \frac{Q}{\mu_o} - 1 \right) + T \left( 1 - \frac{\mu_o^*}{\mu_o} \right), & t_m < t < t_f \end{cases} \quad (4-7)$$

Similarly, one can use the queuing diagrams in Figures 3.8 and 3.11 through 3.18 to derive the queuing delay formulas and the expanded forms of  $s_d(t)$  and  $s_u(t)$  for the rest of the cases of queue evolution with ATIS.

### Numerical Examples

#### CASE I

We consider a three lane highway with a lane capacity of 30 vehicles per minute (total capacity  $\mu_o$  is equal to 90 vehicles per minute). The alternate route has a total capacity  $\mu_2$  of 40 vehicles per minute. Demand  $Q$  is equal to 80 vehicles per minute. Trip time from  $A$  to  $B$  using the freeway,  $T_1$ , is 15 minutes, while  $T_2$  is 25 minutes. An accident occurs on the freeway at point  $C$  at time  $t_o^*$  during off-peak conditions. It takes 10 minutes to travel from  $A$  to  $C$  when there is no queue between  $A$  and  $C$ ,  $\tau=10$  minutes. The accident blocks two out of three lanes and results in a 75% loss in capacity of the freeway. Furthermore, it is estimated that it will take 30 minutes to clear the accident,  $T=30$  minutes. Since  $\tau Q=800$  veh.-min./min. and  $\mu_o^* T=675$  veh.-min./min., then  $\tau Q > \mu_o^* T$ . The initial



delay  $d(t_o^* + \tau)$  is calculated using Eqn. (3-1). The initial delay,  $d(t_o^* + \tau)$  is 21.3 minutes. Since  $d(t_o^* + \tau) > T - r$ , where  $T - r = 10$  minutes, and  $d(t_o^* + \tau) > T^*$ , where  $T^* = 10$  minutes, then Case I applies. As mentioned in Chapter 3 if **ATIS** is used in this base case there are two outcomes of queue evolution: NQ-Case-I and Q-Case-I.

**NQ-CASE-I:** NQ-Case-I applies when the fraction,  $p$ , of the vehicles equipped with **ATIS** is not large enough to cause a queue on Route 2 even if all **ATIS** vehicles are diverted to that route. This is true if  $p$  is less than  $\mu_2 / Q$ , i.e., if  $p$  is less than 0.5 in this case.

A dynamic profile of travel time savings for both guided and unguided traffic along with the queueing diagram when  $p = 0.05$  for this case is illustrated in Figure 4.2. All equipped vehicles are diverted for a period of time  $K$ . Benefits to diverted (or guided) traffic decline to a minimum at the end of the diversion period. This is because diverted travellers are being shifted from the freeway, where the incident queue is diminishing, to the alternate route where there is no queue. Benefits to undiverted (or unequipped) traffic continue to increase till the end of the diversion period  $K$ . As the cumulative number of vehicles that divert to the alternate route throughout the diversion period  $K$  increases, the queue length and the delay on the freeway decreases. This is translated into higher time savings to those who continue to use the freeway. Queueing delay at the incident bottleneck is a function of the history of the arrival curve,  $AI(t)$ . This explains why benefits are not restricted only to travellers who arrive during diversion time  $K$ , but also to those arriving after diversion ends, regardless of whether they are equipped with **ATIS** or not. The queue discharges faster with **ATIS** than without it as shown in Figure 4.2, where the queue vanishes at time  $t_m + \tau$  with **ATIS** and  $t_f + \tau$  without it. As a result, delay on the freeway decreases at a faster rate and the benefits to travellers arriving at  $A$  in time interval  $(t_o^* + K, t_m)$  increase to a maximum at time  $t_m$ . Since the queue would have diminished completely at  $t_f + \tau$  anyway, no benefits accrue to travellers arriving at  $A$  beyond time  $t_f$ .

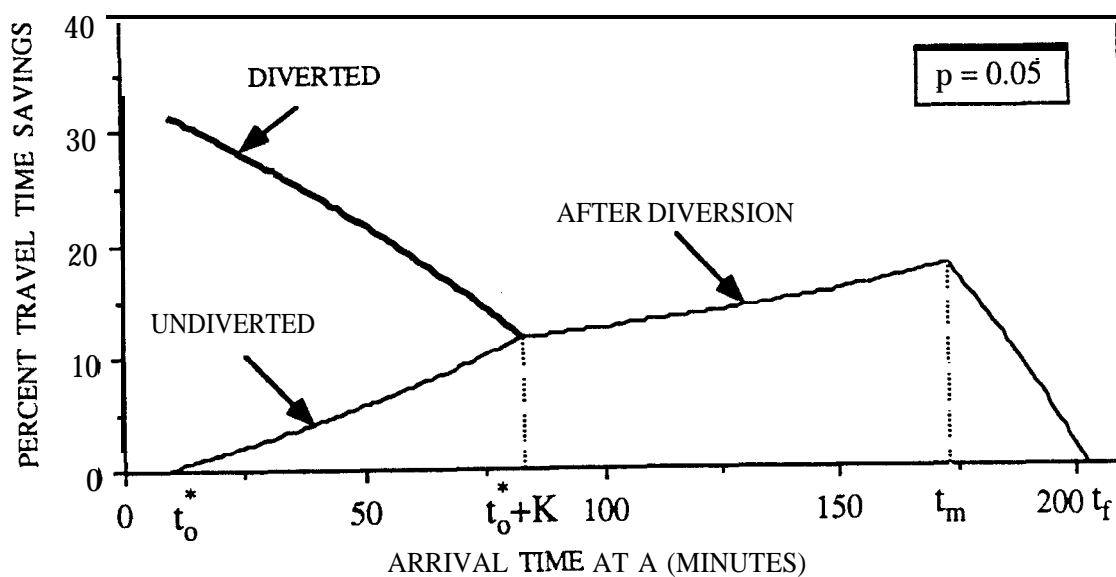
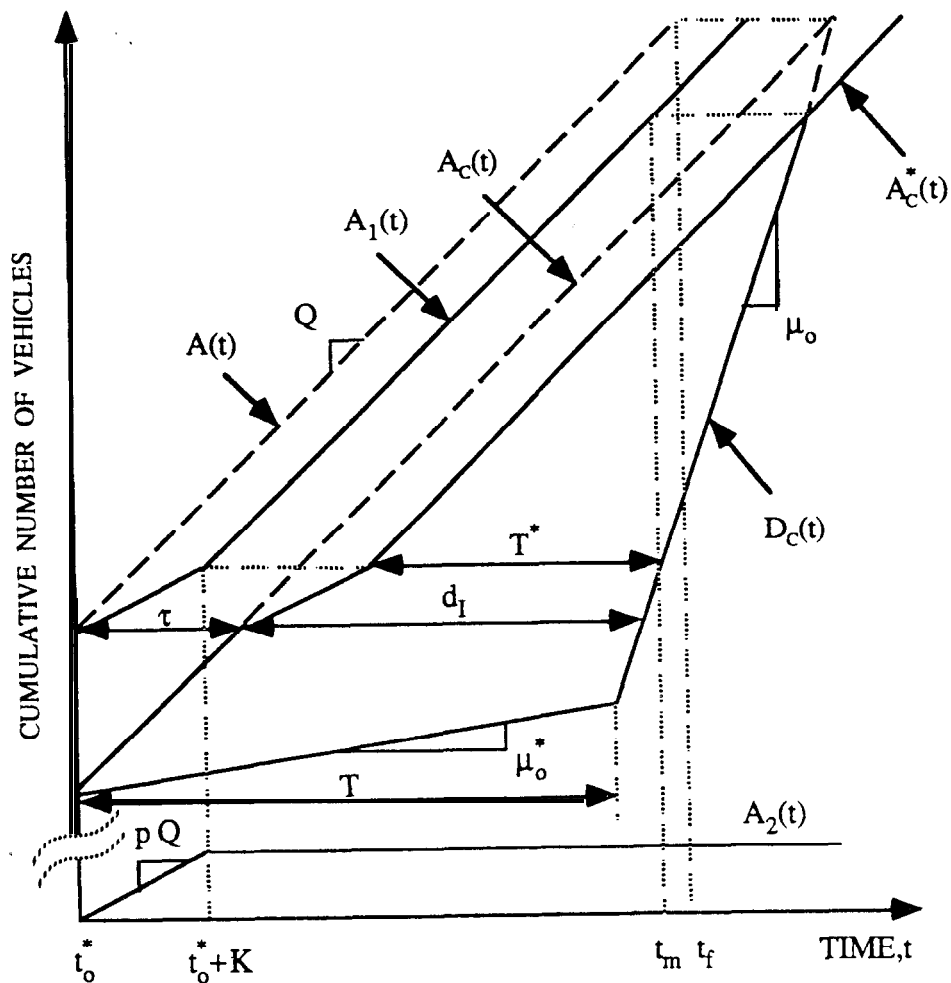


FIGURE 4.2 BENEFITS TO DIVERTED AND UNDIVERTED TRAVELLERS (NQ-CASE-I)

The sensitivity of benefits to  $p$  is illustrated in Figure 4.3. Since there is no queue on the alternate route during diversion, benefits to an equipped vehicle are not affected by how many equipped vehicles are diverted. On the other hand, benefits to undiverted traffic, whether during diversion or after diversion ends, increase as the fraction of equipped vehicles increases. The numerical example illustrates that the maximum benefits are not necessarily gained by equipped travellers who divert to the alternate route; instead, the maximum benefits are gained by travellers arriving after diversion ends.

Q-CASE-I: This case applies when  $p > 0.5$  and is illustrated in Figure 4.4. There are two time intervals during which there is diversion: before equilibrium is achieved between the two routes, and during equilibrium. Diversion in the **first** interval is similar to that of NQ-CASE-I. Basically, all vehicles equipped with **ATIS** are diverted to the alternate route for a period of time  $K$ . In this case, however,  $p$  is large enough to cause a queue on the alternate route creating a configuration of two parallel bottlenecks. Since a queue is forming on the alternate route, an increase in the fraction of diverted vehicles results in a decrease in the benefits to guided traffic. Once equilibrium is reached, the benefits to guided and unguided traffic become identical. It should be noted that in this case the total diversion time,  $(K + \epsilon)$ , is fixed and does not depend on the magnitude of the fraction of equipped vehicles,  $p$ . Furthermore, the benefits to guided and unguided traffic during equilibrium and thereafter are not affected by an increase in  $p$ . Benefits increase during equilibrium because the queue on the alternate route discharges faster than the queue on the freeway. The dotted line in Figure 4.4 shows that even if all vehicles are equipped and therefore diverted to the alternate route during  $K$ , some benefit can still be gained by not diverting. However, this benefit is not as large as the benefit of diversion. In a real life situation small amounts of time savings may not be sufficient to induce travellers to follow instructions to divert, given the possible inconvenience of diversion.

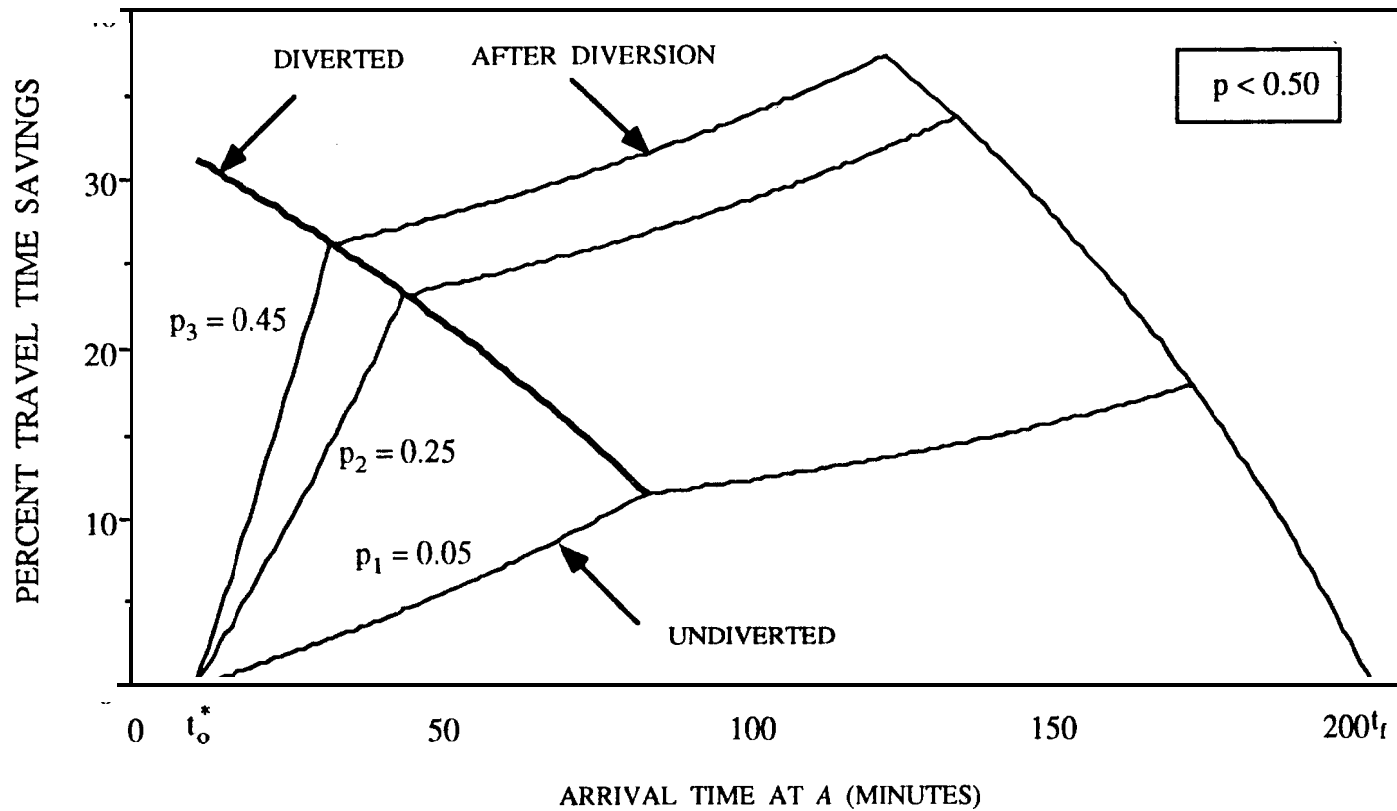


FIGURE 4.3 BENEFITS TO DIVERTED AND UNDIVERTED TRAVELLERS FOR DIFFERENT LEVELS OF  $p$  (NQ-CASE-I)

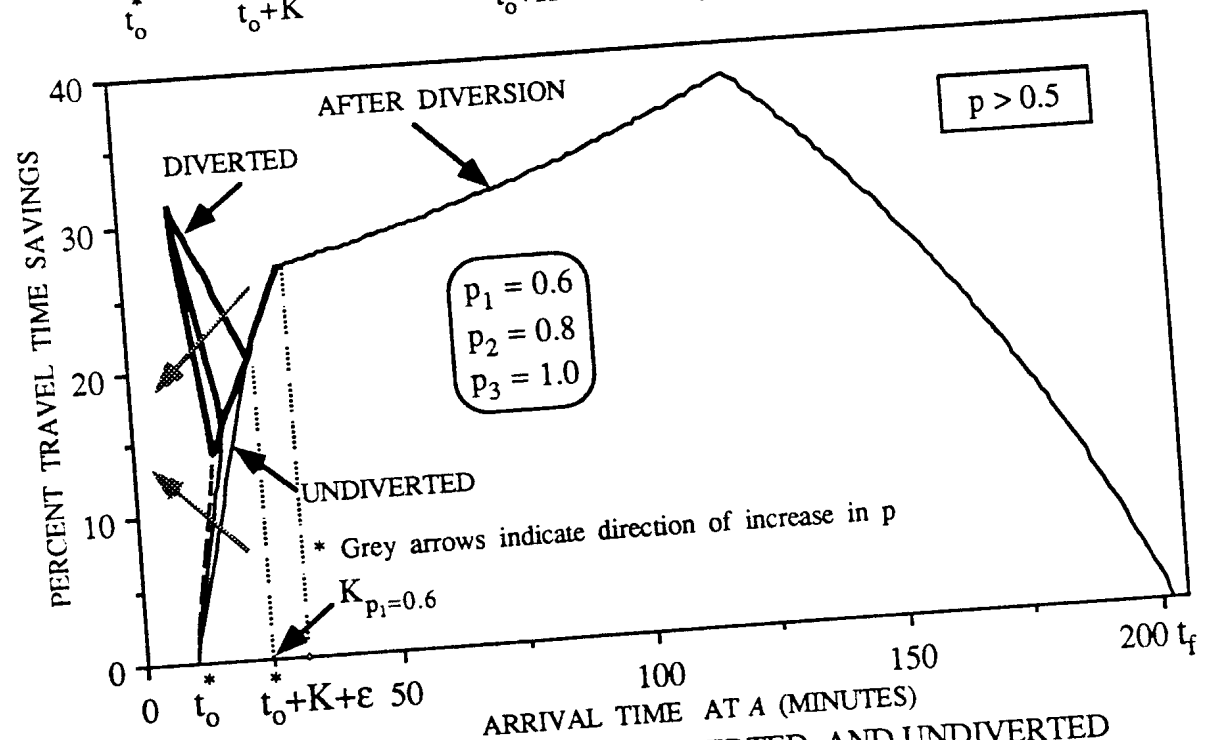
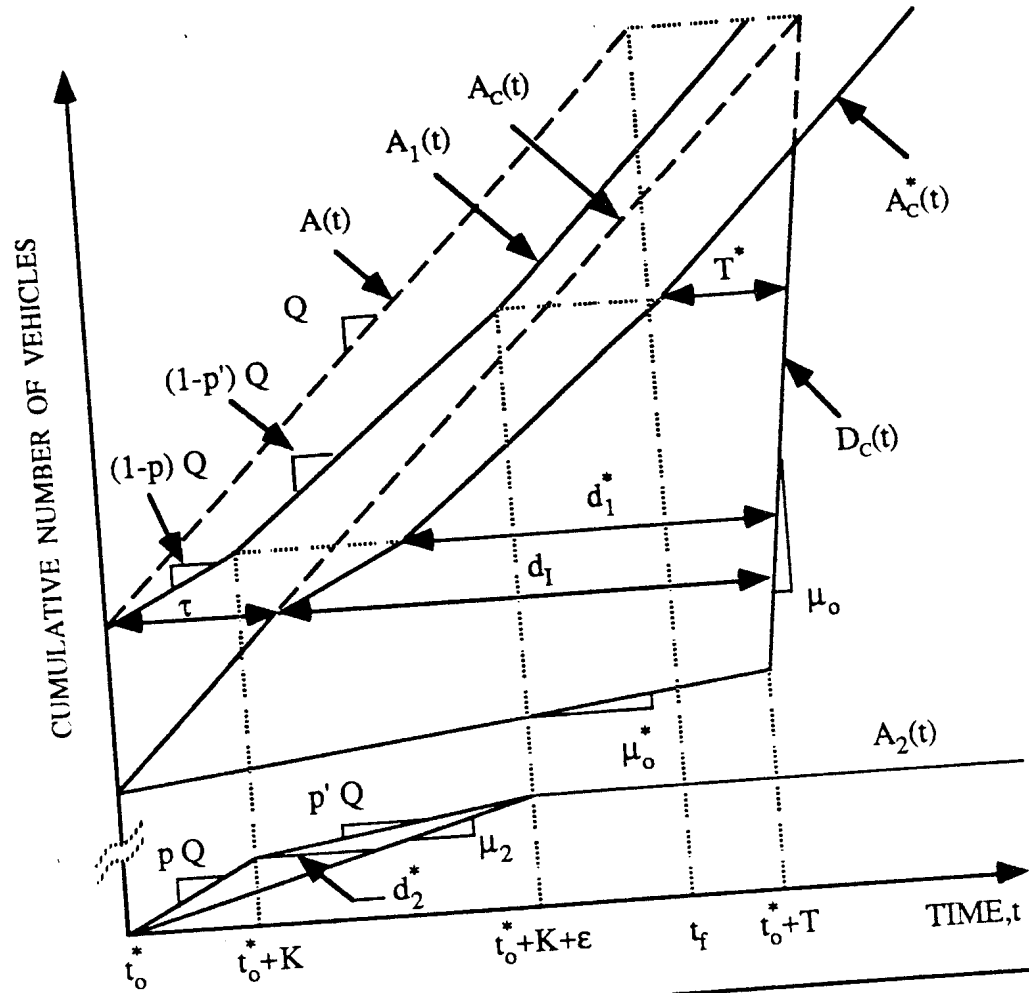


FIGURE 4.4 BENEFITS TO DIVERTED AND UNDIVERTED TRAVELLERS (Q-CASE-1)

In Q-Case-I the trend of the user benefits during the post-diversion period,  $(t_o^* + K + \epsilon, t_f)$ , is similar to that of NQ-Case-I. In both of these cases, a **traveller** who arrives during this period will receive the same benefits whether or not he has **ATIS**. Also, because of the similarity of the queue evolution in all cases during this period (as illustrated in Figures 3.8, 3.9, and 3.11 through 3.18), one can conclude that the post-diversion benefits will always be identical for guided and unguided traffic and that the benefit curve will have the same pattern as it does in the cases: NQ-Case-I and Q-Case-I. Hence, in the rest of the cases, it is sufficient to study the benefit curves only for the periods during which there is diversion.

## CASE II

In Case II travellers arriving at point A after the incident occurs are expected to depart the incident bottleneck while the incident queue is not discharging, i.e.,  $(\mu_o^* T > \tau Q)$ . This occurs if the incident duration in NQ-Case-I is increased and/or if the incident severity is decreased. Hence, Case II can be achieved by setting  $T = 60$  minutes and keeping the same values for all other parameters in the numerical example used in Case I. The four outcomes that result from using **ATIS** in Case II are discussed below.

**NQ1-CASE-II:** This case is similar to NQ-Case-I in the sense that equilibrium is never reached because of the low proportion of **ATIS** guided traffic. This case also applies for  $0 < p < 0.5$ . The benefits to diverted and undiverted traffic are shown in Figure 4.5. Maximum delay,  $d_m$ , occurs at time  $t_o^* + \sigma$ . Note that the benefits to an **ATIS** vehicle increase to a maximum during the first  $\sigma$  minutes of diversion, after which the benefits decline, **similar** to NQ-Case-I. The reason for the increase during  $\sigma$  is that **ATIS** vehicles are being shifted from the freeway, where the queue is building up, to Route 2 where there is no queue. The benefits to unguided traffic follow a trend similar to that of NQ-Case-I

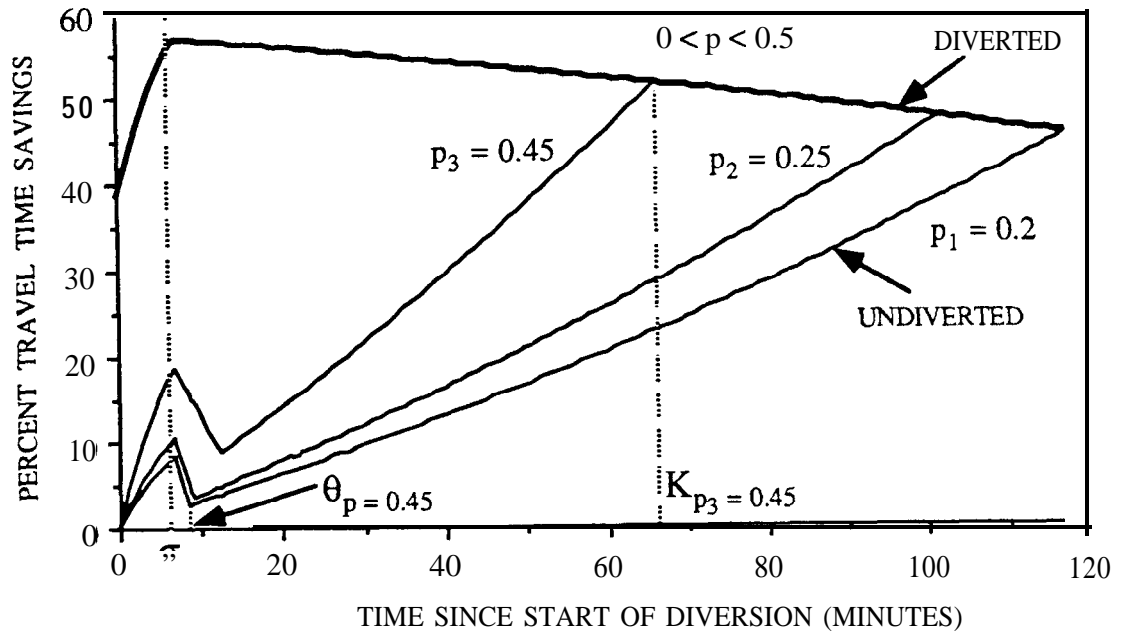
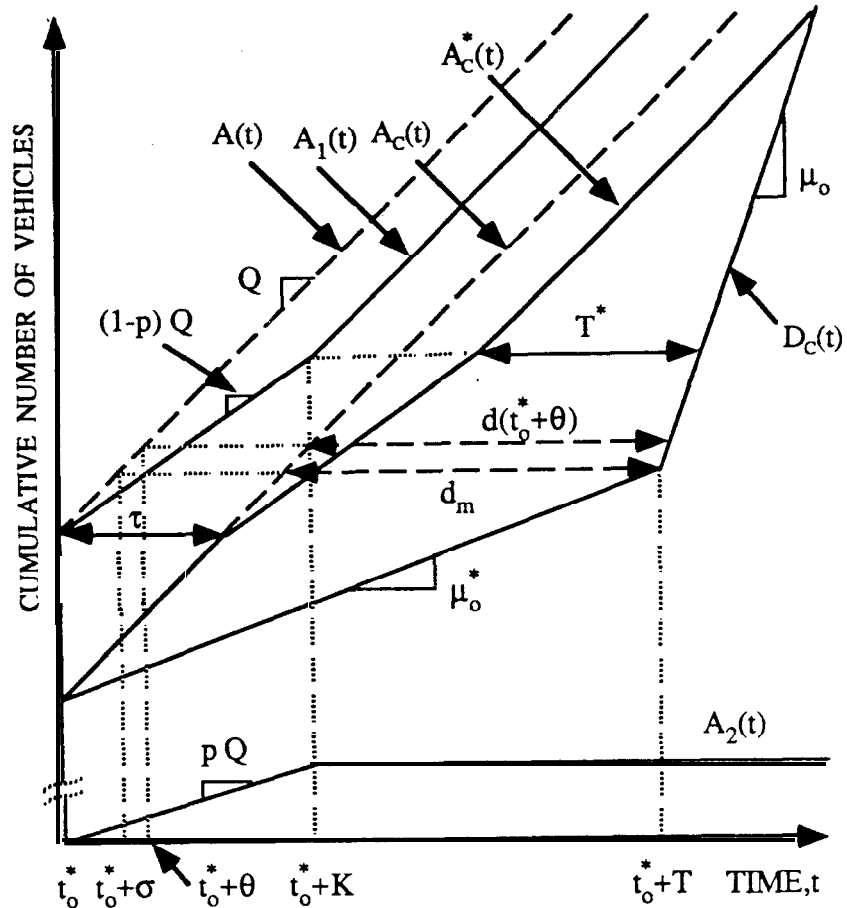


FIGURE 4.5 USER BENEFITS DURING DIVERSION (NQ1-CASE-II)

except for the time interval  $(t_o^* + \sigma, t_o^* + \theta)$ . The change in the trend during this interval is explained as follows: in the absence of **ATIS**, unguided traffic departs the incident bottleneck while the queue is discharging, while if **ATIS** is present the queue will not be discharging.

**Q1-CASE-II:** This case is illustrated in Figure 4.6. It applies when  $0.5 < p < z$ , where  $z$  is calculated using Eqn. (3-30). In this instance  $z$  is 0.74. The proportion of guided traffic is large enough to cause a queue on Route 2 but it is not large enough to initiate an early equilibrium (before the incident queue begins to discharge). Before equilibrium is established, the trend of benefits to diverted and undiverted traffic is similar to that of **NQ1-Case-II**. After equilibrium is established, the trend becomes similar to that of **Q-Case-I**.

**Q2-CASE-II:** This case differs from **Q1-Case-II** in that the proportion of guided traffic is large enough to cause an early equilibrium as shown in Figure 4.7. Therefore, this case applies for  $0.74 < p < 1.0$ . The benefits to diverted traffic increase during the first  $\sigma$  minutes of diversion because the incident queue (without **ATIS**) builds up faster than the queue on the alternate route. The benefits to guided traffic decline after that because guided traffic is shifted from Route 1 when its queue is discharging to Route 2 when its queue is building up. This continues until equilibrium is reached at time  $t_o^* + K$ . During the first equilibrium interval  $(t_o^* + K, t_o^* + K + \epsilon)$ , the queue on Route 2 is not discharging as fast as the queue on Route 1. The picture is reversed, however, during the second equilibrium interval  $(t_o^* + K + \epsilon, t_o^* + K + \epsilon + \lambda)$ .

**NQ2-CASE-II:** This case occurs when the fraction of vehicles equipped with **ATIS** is large enough to cause equilibrium and when there is no queue on Route 2. Note that this case does not apply for the numerical example given for Case II because  $z' = 0.83$ .



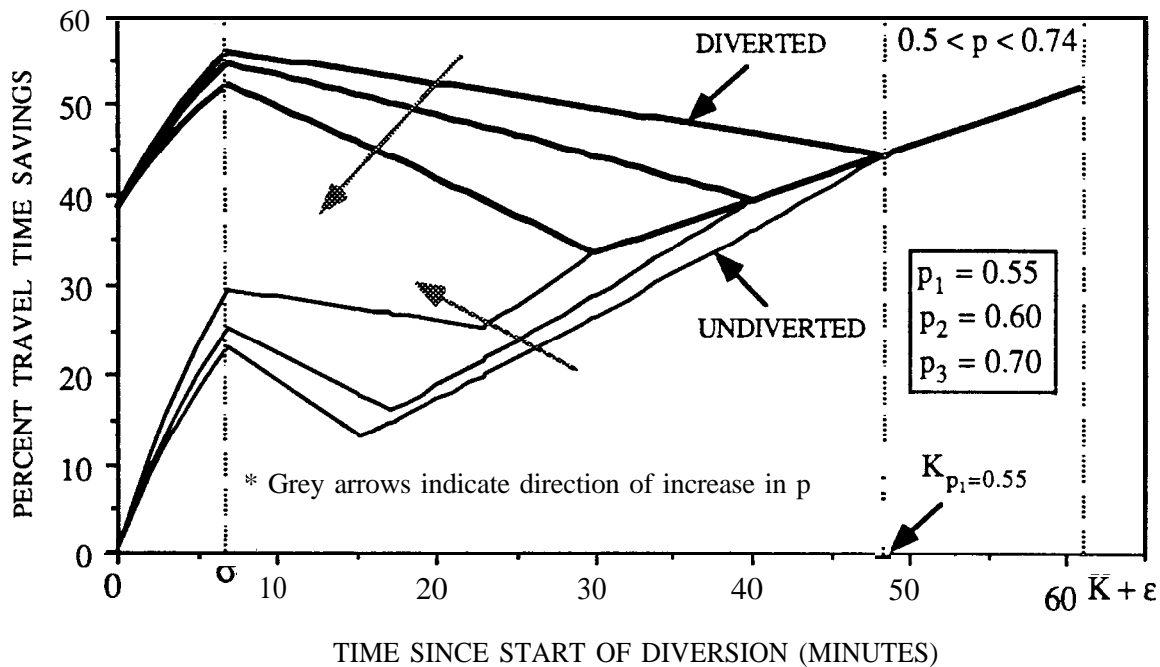
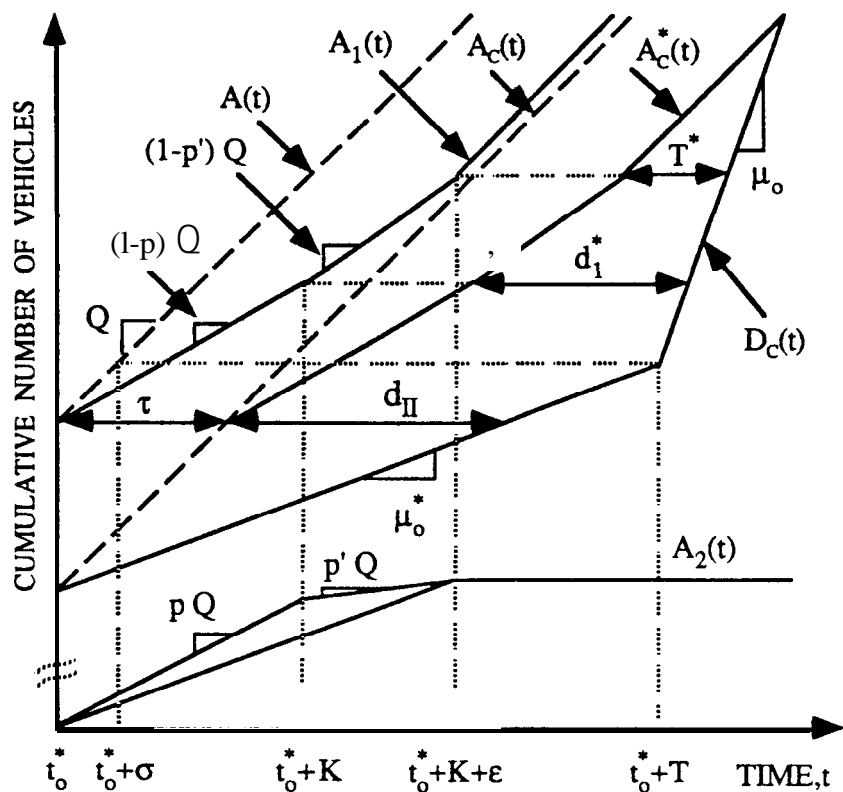


FIGURE 4.6 USER BENEFITS DURING DIVERSION (QI-CASE-II)

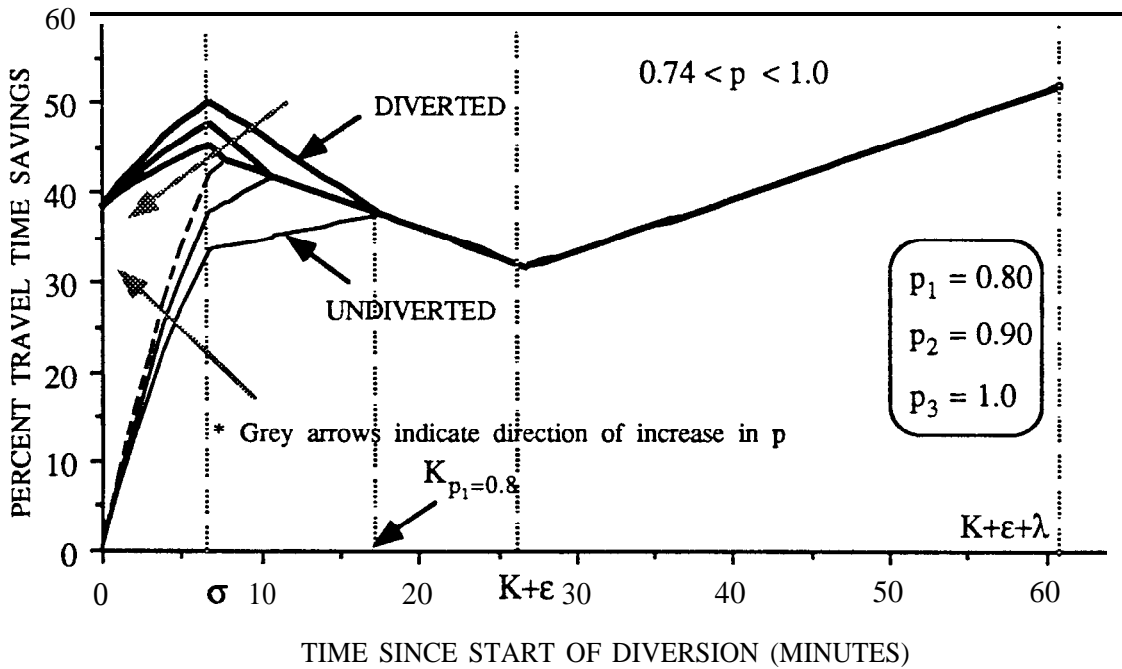
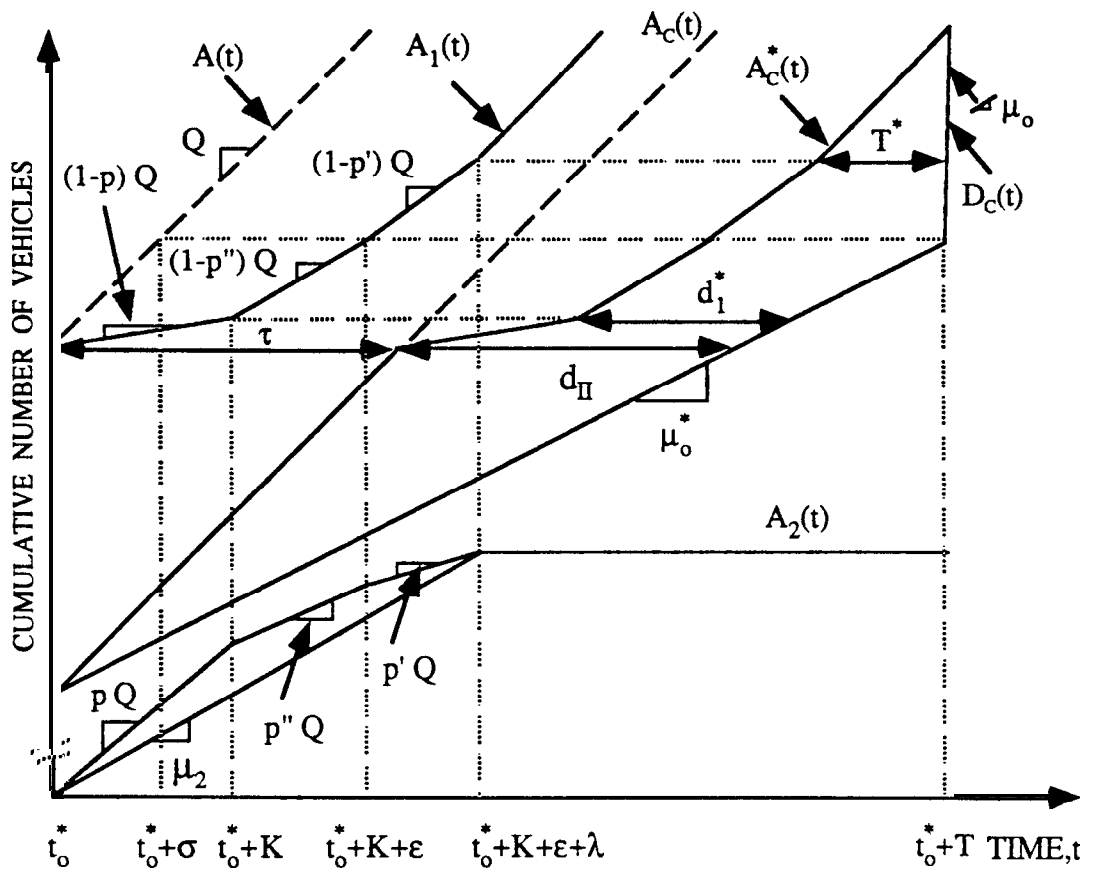


FIGURE 4.7 USER BENEFITS DURING DIVERSION (Q2-CASE-II)

However, if we set  $\mu_2$  to be larger than  $z'Q$ , i.e. if  $\mu_2 > 67$  vpm, then **NQ2-Case-II** will evolve. The benefits to diverted traffic follow a trend that is the same as that of **NQ1-Case-II** and can be explained using similar reasoning (see Figure 4.8). The benefits to unguided traffic continue to increase during time interval  $(t_o^* + \sigma, t_o^* + K)$  because of the quick reduction in the queueing delay on Route 1. This reduction in the delay is a result of the high diversion rate of **ATIS** vehicles to Route 2 to achieve equilibrium. Once equilibrium is achieved at time  $(t_o^* + K)$ , the diversion rate is decreased to maintain equilibrium and the benefits to unguided traffic begin to decrease.

### CASE III

In Case III the incident is not severe enough to warrant immediate diversion. Instead, diversion does not start until time  $t_o^* + \alpha$ . This incident base case occurs if we set  $T = 60$  minutes,  $T^* = 20$  minutes,  $\mu_o^* = 30$  vpm, and keep the rest of the parameters' values as in Case I. The four outcomes of queue evolution that result when **ATIS** is used with this base case are discussed below.

**NQ1-CASE-III:** This case is shown in Figure 4.9. Note that equilibrium is established momentarily when diversion starts at time  $t_o^* + \alpha$ . It is not possible to keep this equilibrium, however, because of the insufficient number of **ATIS** vehicles. The gap between the benefits for diverted and undiverted traffic increases to a maximum after  $\sigma$  minutes of diversion. The trend of the benefits thereafter is similar to that of **NQ1-Case-II**.

**Q1-CASE-III:** This case is shown in Figure 4.10. It is similar to **NQ1-Case-III** except that the number of diverted **ATIS** vehicles is large enough to cause a queue on Route 2. Note that equilibrium is achieved momentarily at time  $t_o^* + \alpha$ , before the incident queue begins to discharge. The proportion of **ATIS** guided traffic is insufficient to maintain

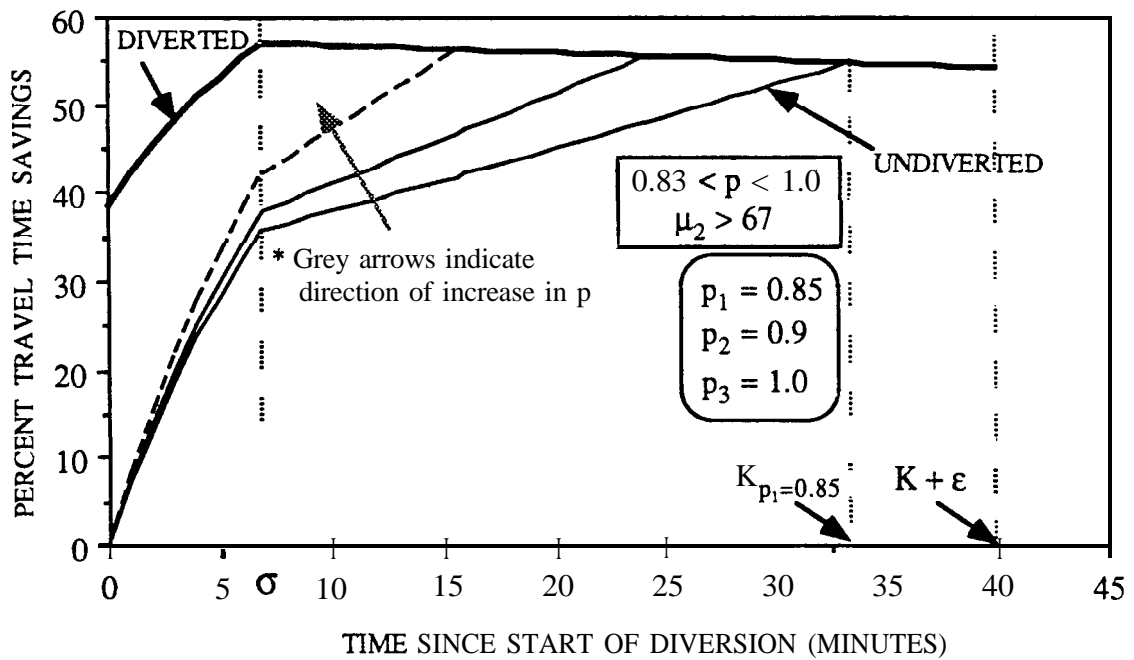
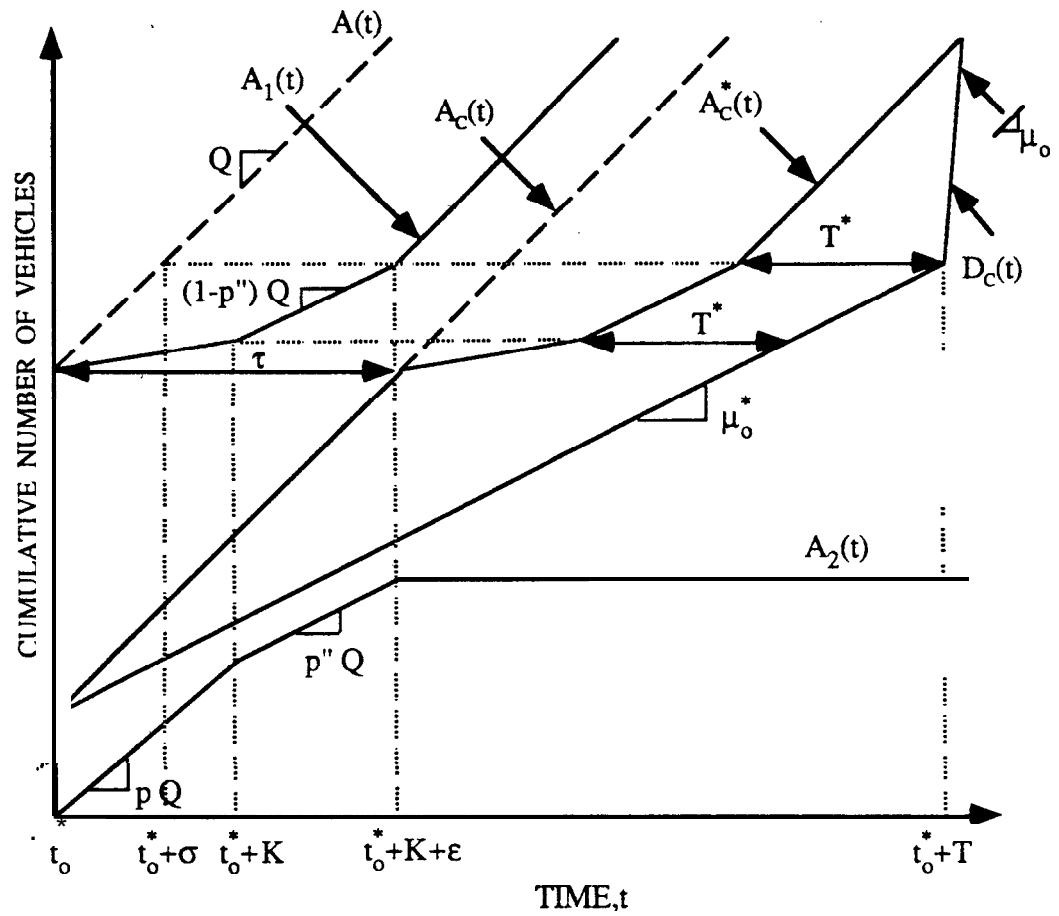


FIGURE 4.8 USER BENEFITS DURING DIVERSION (NQ2-CASE-II)

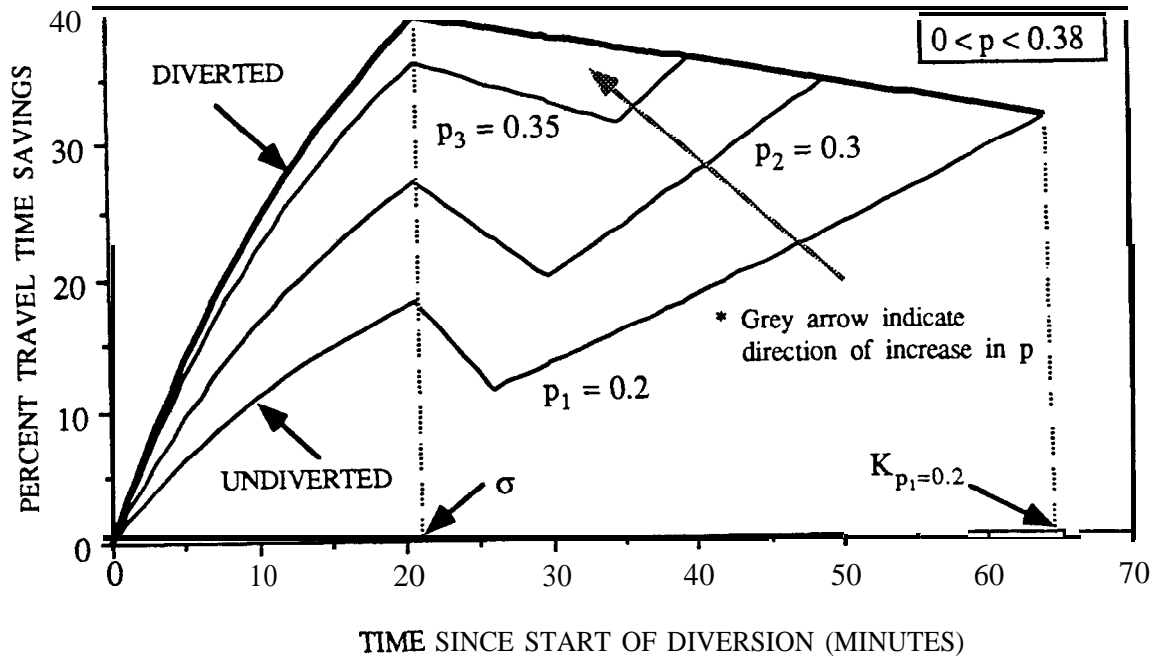
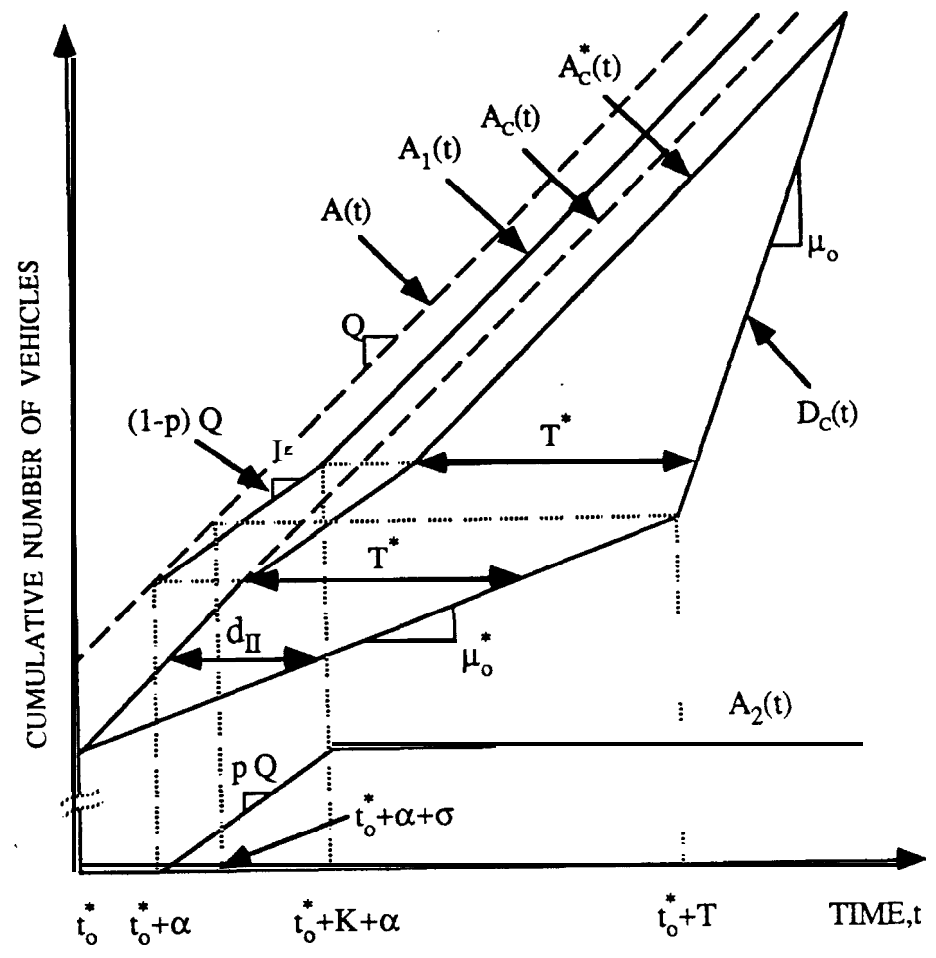


FIGURE 4.9 USER BENEFITS DURING DIVERSION (NQ1-CASE-III)

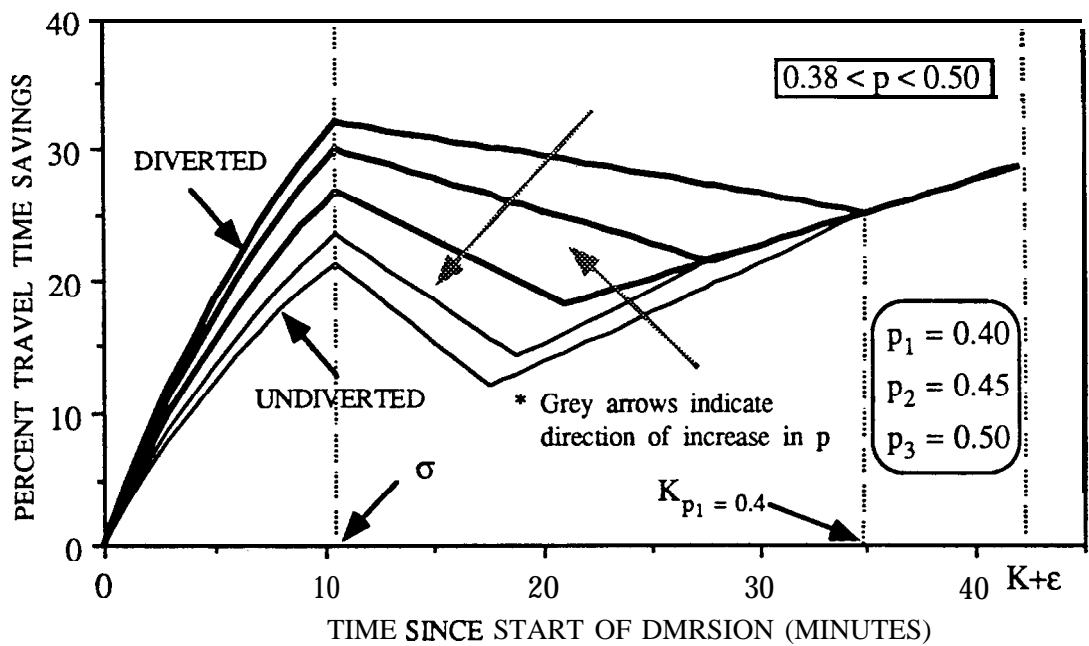
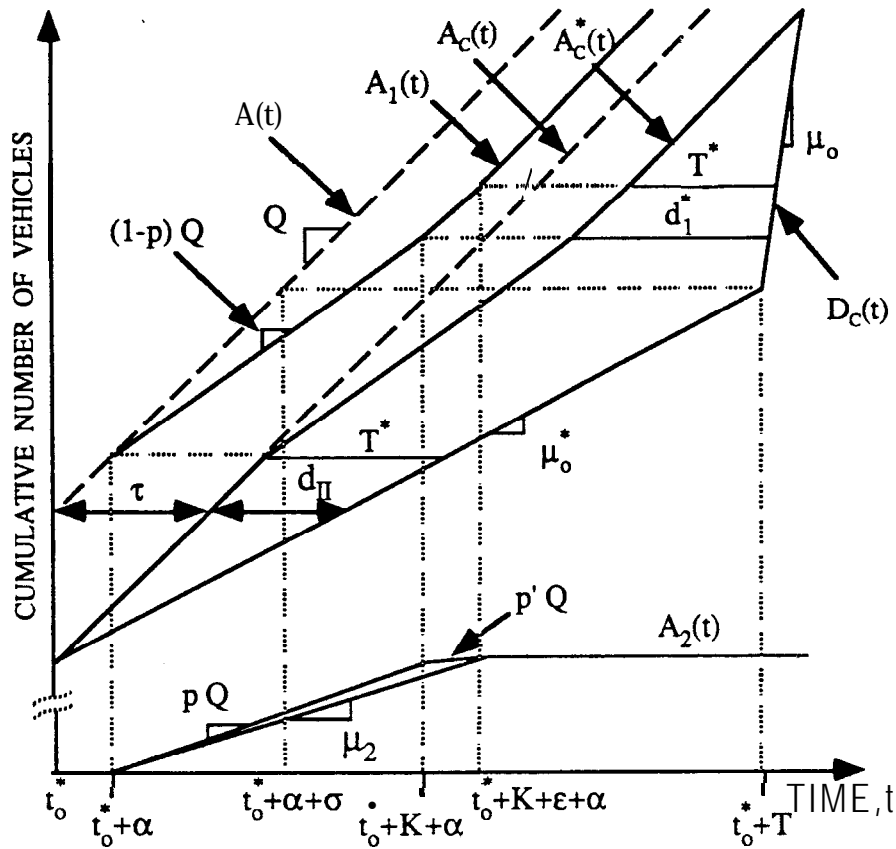


FIGURE 4.10 USER BENEFITS DURING DIVERSION (QI-CASE-III)

equilibrium while the incident queue is not discharging. The trend of benefits in this case is self explanatory.

**Q2-CASE-III:** This case will result if the conditions of Q1-Case-III are valid, with one additional condition: that the proportion of guided traffic is large enough to maintain equilibrium once it is achieved, as shown in Figure 4.11. Equilibrium continues for the entire period of diversion in this case and the trend of the benefits can be explained using reasoning similar to the previous cases.

**NQ2-CASE-III:** This case is shown in Figure 4.12. The only difference between this case and NQ1-Case-III is that the fraction of guided traffic in this case is large enough to keep equilibrium once it is established. Note that this case does not evolve in the numerical example given in Case III mentioned earlier because the minimum fraction of vehicles needed to initiate equilibrium (when there is no queue on Route 2) is equal to 0.63. This case will evolve if we set  $\mu_2 > 50$  vpm or if  $0.63 < p < 1.0$ . Equilibrium starts at time  $t_o^* + \alpha$  and continues until the incident queue begins to discharge and the freeway reverts to being faster again at time  $t_o^* + \alpha + \epsilon$ . Note that because of equilibrium, benefits to guided and unguided traffic are identical and are not influenced by any increase in  $p$ , the fraction of vehicles equipped with ATIS.

### **General Characteristics of ATIS User Benefits**

Similarity of the trends of the user benefits among the different cases suggests the general characteristics described by Figure 4.13. When the term “queue is discharging” is used it means that the queue is discharging at the time when the travellers' are departing from the incident bottleneck. The general characteristics of ATIS user benefits are summarized as follows:

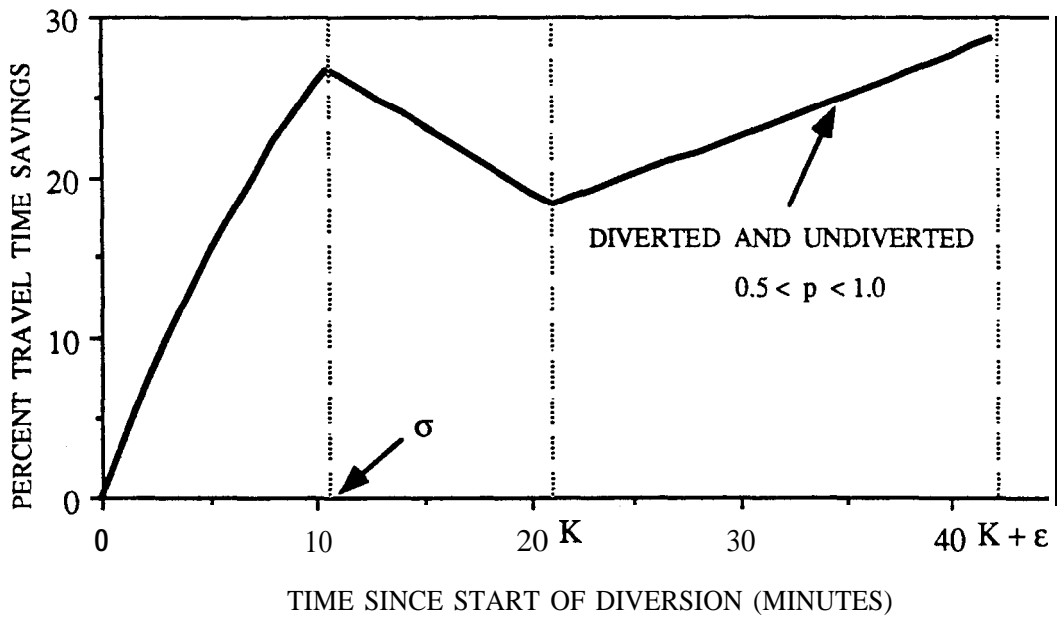
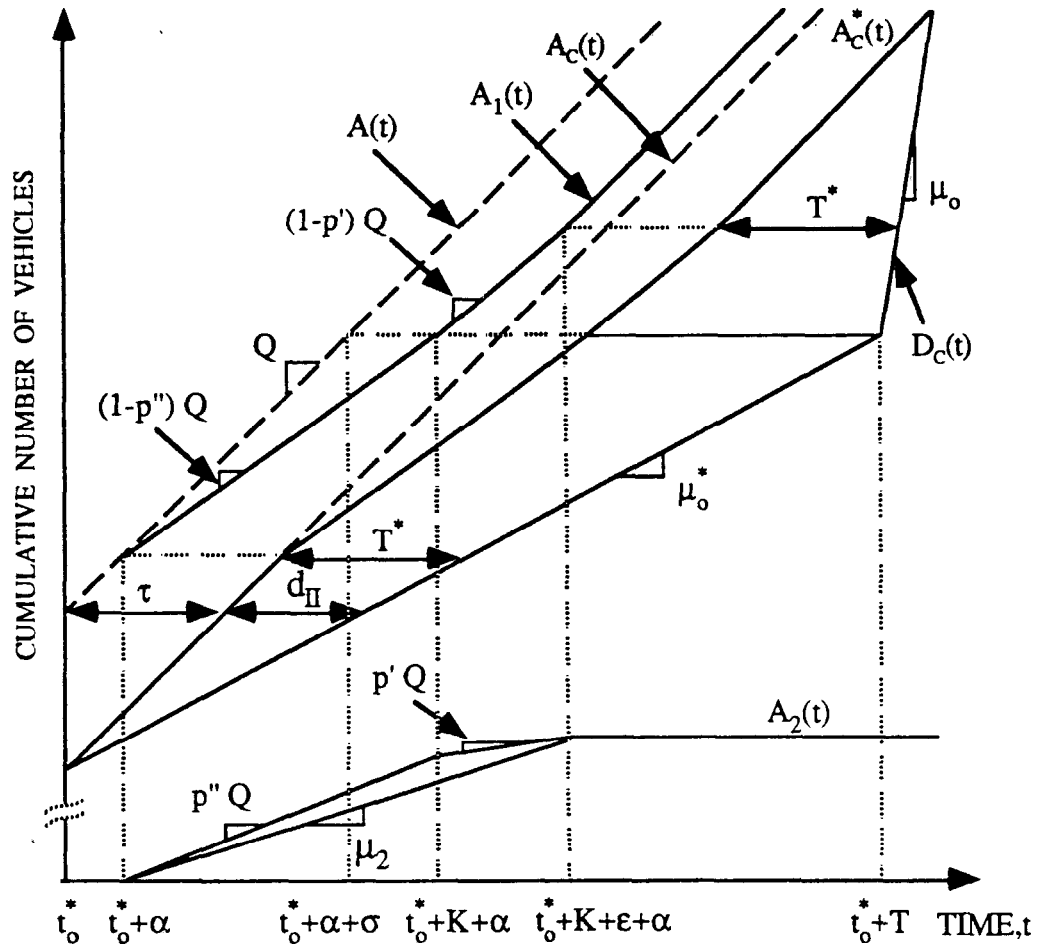


FIGURE 4.11 USER BENEFITS DURING DIVERSION (Q2-CASE-III)



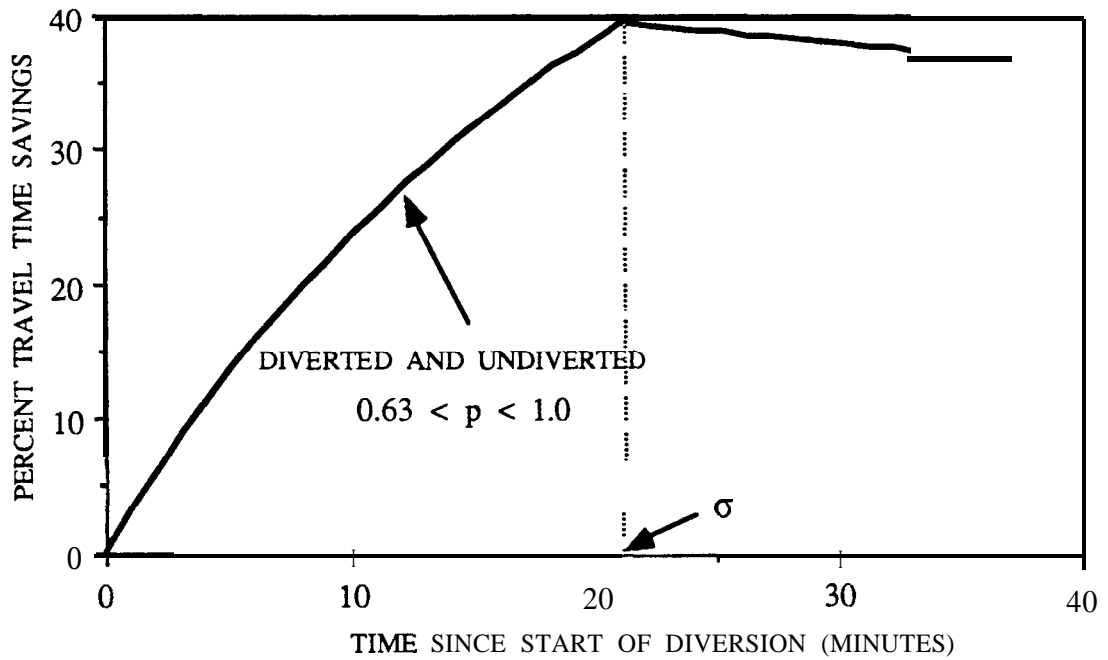
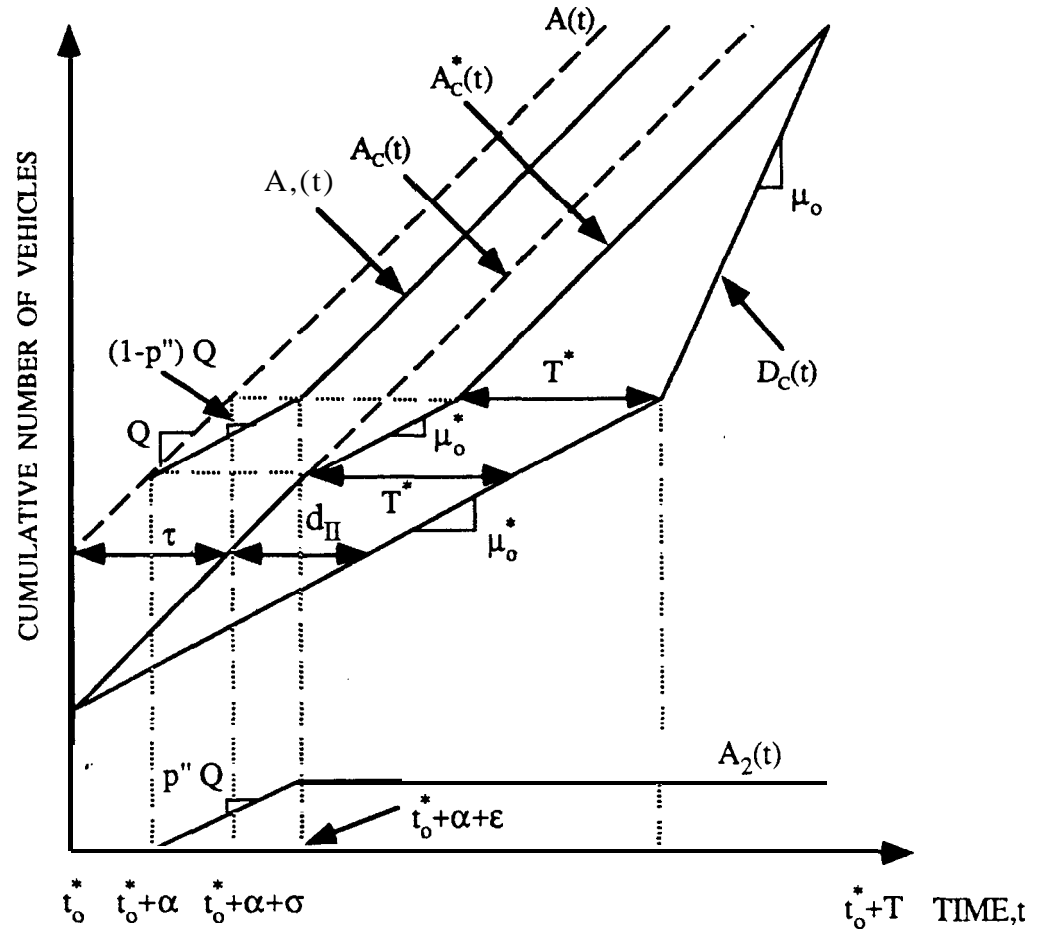


FIGURE 4.12 USER BENEFITS DURING DIVERSION (NQ2-CASE-III)

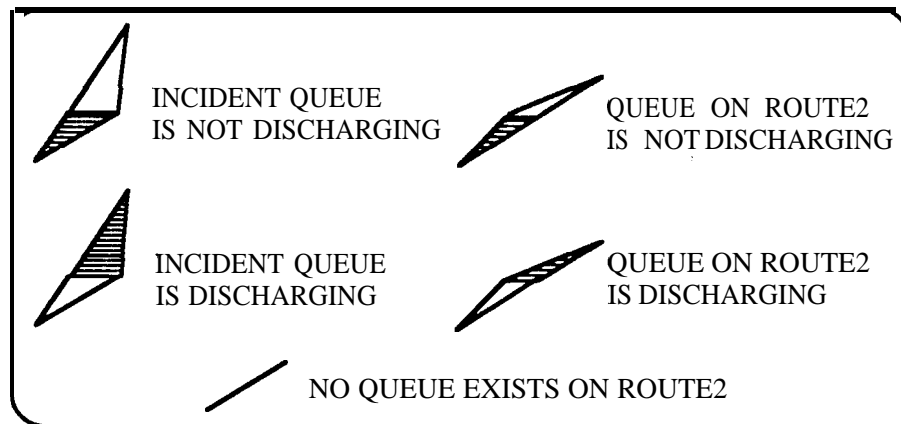
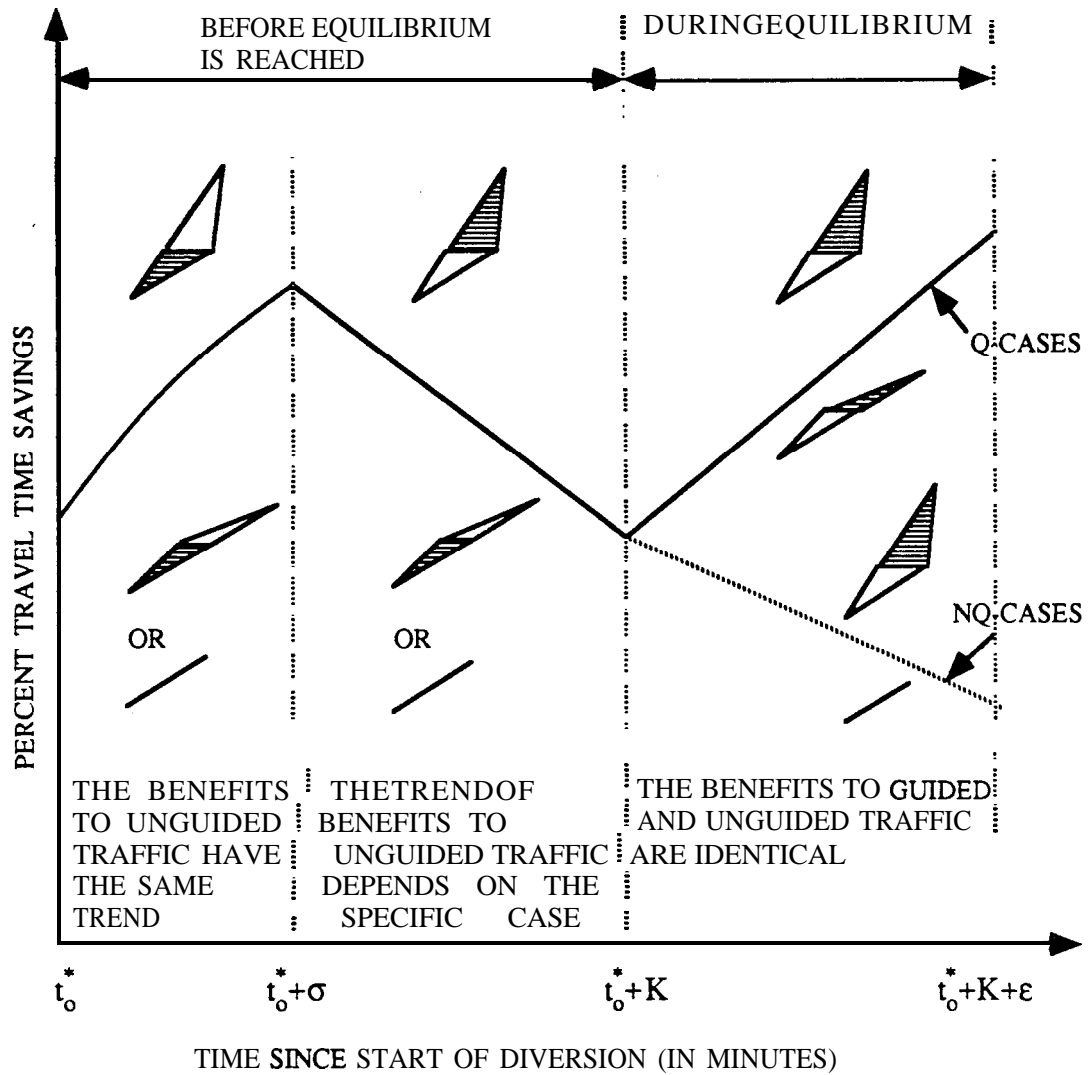


FIGURE 4.13 GENERAL CHARACTERISTICS OF ATIS USER BENEFITS

1. As long as the incident queue on Route 1 has not begun to discharge, **ATIS** benefits to both guided and unguided traffic continue to increase with the **arrival** time at A.
2. When the incident queue on Route 1 begins to discharge, the benefits to guided traffic start to decline until equilibrium is achieved, or until diversion ends, whichever comes first. The reason for this decline is that diverted traffic is shifted to Route 2, where either the queue is not discharging or it does not exist. The benefits to unguided traffic either continue to increase, or **first** decrease and then increase, until equilibrium is achieved or until diversion ends, whichever comes first.
3. Once equilibrium is reached, the benefits to guided and unguided traffic become identical. If there is no queue on Route 2, then the benefits continue to decrease until equilibrium ends. If there is a queue on the alternate route, then the benefits start to increase again until equilibrium ends. The reason for this is that the queue on Route 2 is discharging faster than the queue on Route 1<sup>1</sup>.
4. As long as equilibrium is not reached, guided traffic is better off than unguided traffic. But when there is a queue on the alternate route, and the fraction of vehicles equipped with **ATIS** is increased, then guided traffic becomes less better off than unguided.

### **User Perception of ATIS Benefits**

It is obvious that whenever **travellers** equipped with **ATIS** follow instructions and divert, unequipped travellers also receive benefits. It was found that in some cases, for considerable durations of time, the benefits to a non-guided **traveller** may be comparable (if not equal) in magnitude to the benefits to a guided **traveller**. This is a major concern for the

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<sup>1</sup> This rule is slightly different for **Q2-Case-II**, where equilibrium occurs during two time intervals. Benefits decrease in the first equilibrium interval and then increase in the second until equilibrium is over.

marketing of **ATIS** technology. The extent to which **ATIS** technology penetrates the market mainly depends on how its potential users perceive its benefits. In this section we discuss two issues that relate to the user perception of **ATIS** benefits: 1) when and how much of the time being guided with **ATIS** makes it better off than being unguided?, and 2) how the perception of **ATIS** benefits is influenced by incremental deployment of this technology?

In the previous section it was found that guided traffic is better off than unguided traffic as long as equilibrium has not been reached. This occurs during the **first** diversion period  $K$ . The maximum duration of period  $K$ , expressed as a percentage of the total time period during which there are benefits, is used to represent the best chance for guided traffic to be better off than unguided. Since  $K$  is inversely proportional to the fraction  $p$ , maximum  $K$  occurs when  $p$  is smallest. In the numerical example of NQ-Case-I, maximum  $K$  occurs when  $p$  is very small ( $p=0$ ) and is equal to 103 minutes, while the total time during which there are benefits ( $t_f - t_o^*$ ) is equal to 193 minutes. Thus, the numerical example in NQ-Case-I illustrates that at best during 53% of the time guided travellers can be better off than unguided travellers. In the numerical example of Q-Case-I, maximum  $K$  occurs when  $p=0.5$  and is equal to 21 minutes, while the total time during which there are benefits ( $t_f - t_o^*$ ) is equal to 193 minutes. Therefore, in this case, at best during 11% of the time guided travellers can be better off than unguided travellers. Compared to NQ-Case-I, the best chance to be better off has decreased as much as five times. Not only that, but also the margin by which guided traffic is better off than unguided is much less in this case than it is in NQ-Case-I (see Figure 4.14).

The maximum length of diversion period  $K$  is compared among the cases, and the results are shown in Figure 4.15. It is clear that increasing the proportion of guided traffic reduces its chance of being better off than unguided by several fold if

1) a transition is made from a NQ-type case to a Q-type case, or if

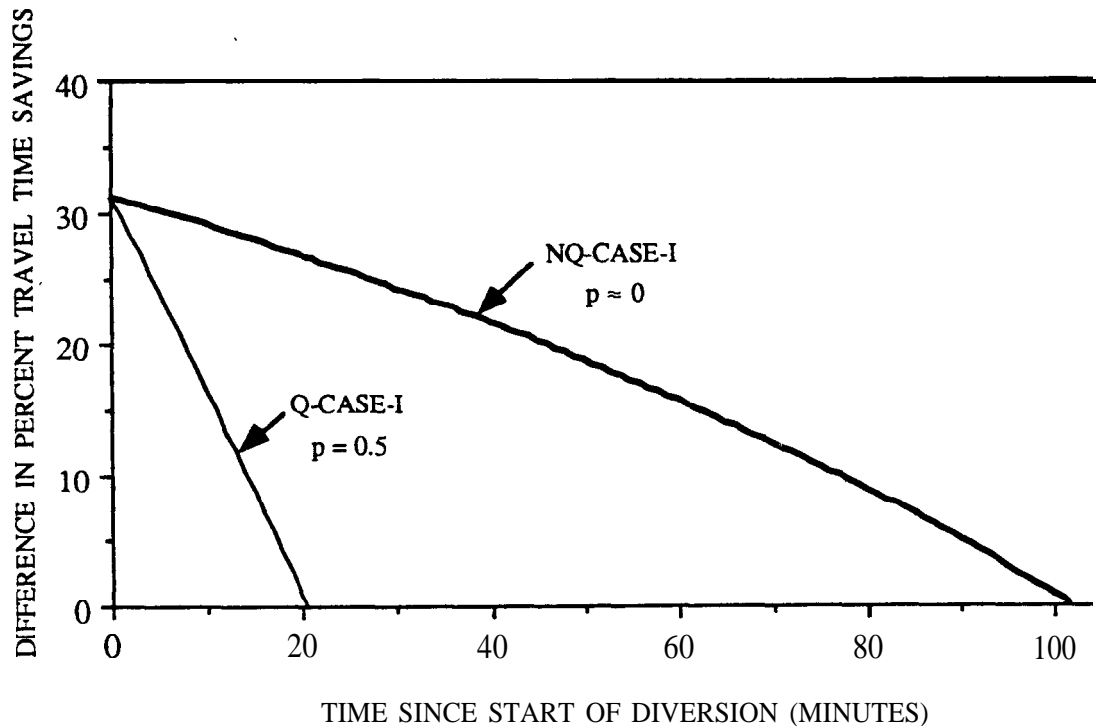


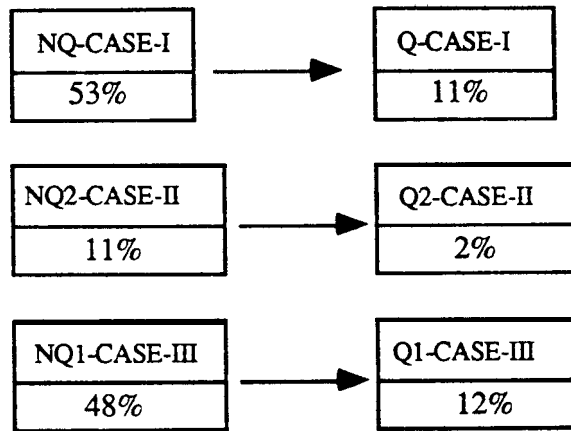
FIGURE 4.14 DIFFERENCE IN BENEFITS BETWEEN GUIDED AND UNGUIDED TRAFFIC (NQ-CASE-I AND Q-CASE-I)

2) a transition is made from a case where equilibrium cannot be achieved to a case where it can be achieved.

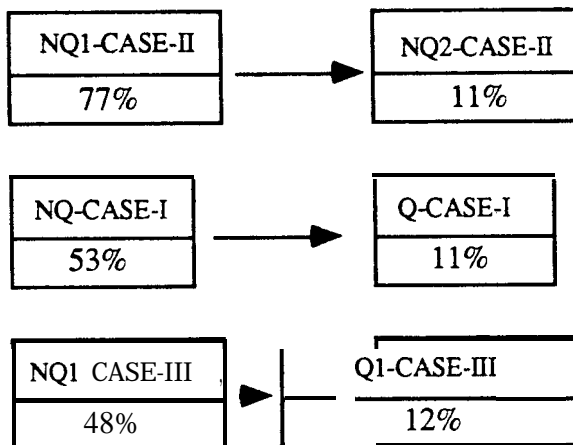
Note that the transition from a case with late equilibrium to a case with early equilibrium also reduces this chance but to a much lesser extent.

The second issue of user perception is related to the diminishing returns of **ATIS** as it incrementally penetrates the market. In the previous analysis, user benefits were compared to the situation before **ATIS** is introduced, i.e., when  $p=0$ . It is reasonable to use this as a reference to calculate the percent travel time savings accrued to the first increment of **ATIS** users. However, after the first increment is introduced, potential users perceive the benefits of **ATIS** differently. Since unequipped travellers already receive free benefits, their incentive to buy the equipment is a function of the additional benefits that they gain if they use **ATIS**. Therefore, calculation of the percent travel time savings to

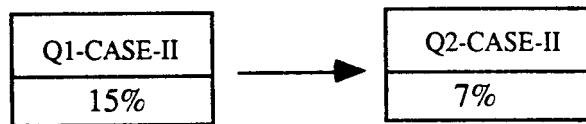
TRANSITION FROM A NQ-TYPE CASE TO A Q-TYPE CASE



TRANSITION FROM A CASE WITH NO EQUILIBRIUM TO A CASE WITH EQUILIBRIUM



TRANSITION FROM A CASE WITH LATE EQUILIBRIUM TO A CASE WITH EARLY EQUILIBRIUM



LEGEND

CASE NAME
PERCENT OF THE TIME GUIDED TRAFFIC IS BETTER OFF THAN UNGUIDED

FIGURE 4.15 TRANSITION BETWEEN CASES AS THE MARKET PENETRATION OF ATIS INCREASES

guided traffic will be based on a case where  $p > 0$ . This reflects the decrease in willingness to buy ATIS by its potential users. Figures 4.16 illustrates the impact of the incremental market penetration on the benefits to guided and unguided traffic for NQ-Case-I. The

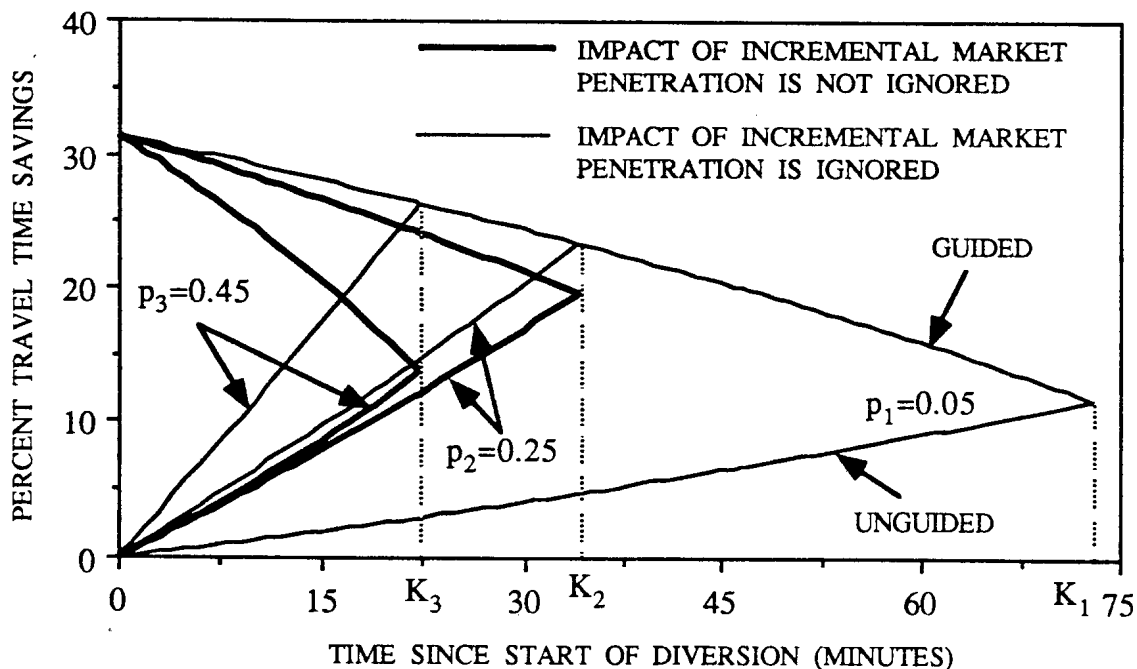


FIGURE 4.16 IMPACT OF THE INCREMENTAL MARKET PENETRATION ON ATIS USER BENEFITS (NQ-CASE-I)

market penetration of ATIS starts with 5% level, later on it increases to 25% and then to 45% level. For example, travel time savings for the 25% level are referenced to a base case where  $p=5%$  instead of 0%. For comparison, this figure also shows the benefits when the impact of the incremental market penetration is ignored. Note that when this impact is not ignored, the perceived benefits to guided traffic decrease as the level of the market penetration increases. Note also that the perceived benefits to unguided traffic increase with  $p$  at a slower rate than if this impact has been ignored.

## 4.2 System Benefits

In this section we investigate system benefits, i.e, the total travel time savings in the corridor that result from diversion of **ATIS** vehicles to the alternate route. System benefits are calculated as the net reduction in total queueing delay minus the net increase in total free flow travel time.

We illustrate the methodology of calculating system benefits using Q-Case-I with a numerical example. Queue evolution for this case is reproduced in Figure 4.17. System benefits are given by:

$$S = AR - \Delta TT \quad (4-8)$$

where,

$S$  : total travel time savings (or system benefits)

$AR$  : net reduction in total queueing delay

$\Delta TT$  : net increase in total free flow travel time

The net reduction in total queueing delay is equal to the difference between the two shaded areas shown in Figure 4.17, hence

$$\Delta R = R_1 - D_2 \quad (4-9)$$

where,

$R_1$  : reduction in total queueing delay on Route 1

$D_2$  : increase in total queueing delay on Route 2.

Net increase in total free flow travel time  $\Delta TT$  is given by:

$$\Delta TT = TT_2^i + TT_1^i - TT_1 \quad (4-10)$$

where,

$TT_1$  : Total free flow travel time on Route 1 without **ATIS**

$TT_1^i$  : Total free flow travel time on Route 1 with **ATIS**

$TT_2^i$  : Total **free** flow travel time on Route 2 with **ATIS**



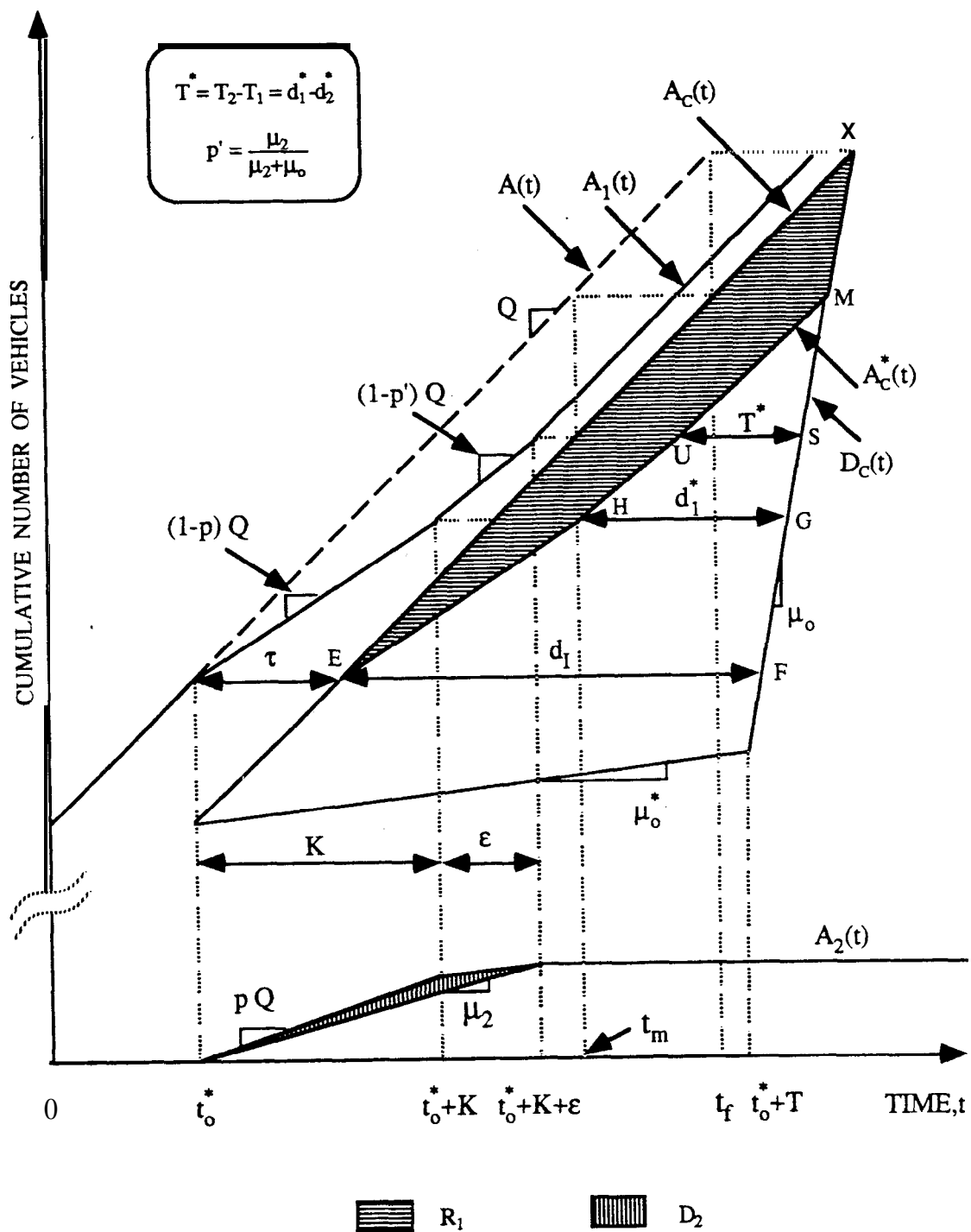


FIGURE 4.17 EVALUATION OF ATIS SYSTEM BENEFITS (Q-CASE-I)

Further, we find the expanded forms of AR and ATT. Reduction in delay on Route 1,  $R_1$ , is given by:

$$R_1 = \mathcal{A}(\text{EFX}) - \mathcal{A}(\text{EFGH}) - a(\text{HGSU}) - a(\text{USM}) \quad (4-11)$$

where areas EFX, EFGH, HGSU, and USM can be found from the geometry of the queueing diagram as

$$\mathcal{A}(\text{EFX}) = \frac{1}{2} \left( \frac{\mu_o Q d_1^2}{\mu_o - Q} \right)$$

$$a(\text{EFGH}) = \frac{1}{2} (1-p) Q K (d_1 + d_2)$$

$$a(\text{HGSU}) = \frac{1}{2} (1-p') Q \epsilon (d_1 + T^*)$$

$$\mathcal{A}(\text{USM}) = \frac{1}{2} \left( \frac{\mu_o Q T^{*2}}{\mu_o - Q} \right)$$

where  $d_1$ ,  $d_1^*$ ,  $p'$ ,  $K$ , and  $\epsilon$  are given by (3-1), (3-4), (3-9), (3-10), and (3-11), respectively.

If there is a queue on Route 2, then delay  $D_2$  is given by:

$$D_2 = \frac{1}{2} d_2^* Q (p K + p' \epsilon) \quad (4-12)$$

where  $d_2^*$  is given by (3-7).

Each vehicle that diverts from Route 1 to Route 2 incurs an increase in its travel time that equals  $T^*$ . A total of  $pKQ$  ATIS vehicles are diverted to Route 2 before equilibrium is reached and a total of  $p'Q\epsilon$  ATIS vehicles are diverted during the period of equilibrium. Since the total free flow travel time for unequipped vehicles does not change, ATT is given by:

$$\Delta TT = T^* Q (p K + p' \epsilon) \quad (4-13)$$

Substituting for  $R_1, D_2$  and  $\Delta TT$  into (4-8) and simplifying results in system benefits  $S$

$$S = Q \left[ \frac{\mu_o}{2(\mu_o - \sigma)} (d_1^2 - T^{*2}) - (pK + p'\epsilon) \left( T^* + \frac{d_2^*}{2} \right) \right] - \frac{1}{2} \left[ (1-p)QK(d_1 + d_1^*) + (1-p')Q\epsilon(d_1^* + T^*) \right] \quad (4-14)$$

### Evaluation of System benefits

System benefits are evaluated at a certain level of  $p$ . It was found in Chapter 3 that incidents with identical parameters but different levels of  $p$  could result in different cases of queue evolution. These cases were identified by threshold values of  $p$ . The results of the system benefits for the three base cases mentioned in Chapter 3 are discussed below.

Figure 4.18 depicts system benefits for Case-I as the fraction of vehicles equipped with ATIS increases from 0 to 1. The base value for percent travel time savings is the total travel time in the corridor from A to B when there is an incident but no ATIS. Fig. 4.18 illustrates that system benefits increase with  $p$  as long as  $p$  is less than some critical value,  $p_c$ , where  $p_c = \mu_2/Q$ . Note that  $p_c$  equals 0.5 in this case. The system benefits become independent of  $p$  and stay at a constant level when  $p$  is larger than 0.5, or when a queue starts to form on the alternate route. This implies that system benefits are maximized when  $p$  is equal to  $p_c$ . Diversion of more than  $p_c$  will only reduce the average benefits for ATIS travellers and does not add any system gain.

The system benefits for Cases II and III were also investigated using various numerical examples. The objective of this investigation is to analyze the sensitivity of system benefits to, the fraction of vehicles equipped with ATIS,

- when there is a transition from a case where only the incident bottleneck is busy to a case where bottlenecks on both routes are busy, i.e. a transition from a NQ-type case to a Q-type case;

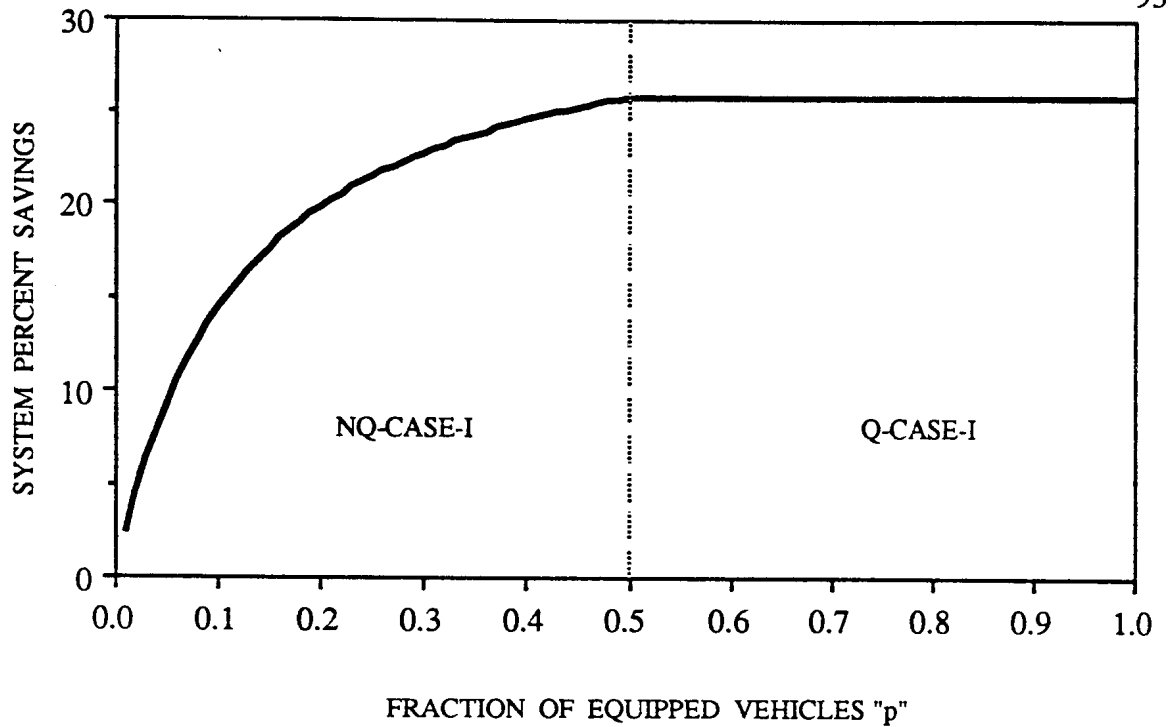


FIGURE 4.18 SYSTEM BENEFITS VERSUS "p" (NQ-CASE-I AND Q-CASE-I)

- when only the incident bottleneck is busy but there is a transition from a case where equilibrium cannot be achieved to a case where it can be achieved; and
- when there is a transition from a Q-type case with late equilibrium to a Q-type case with early equilibrium.

The results are shown in Figures 4.19 through 4.22. The results can be summarized as follows:

1. The results of Cases II and III are consistent with the result found in Case-I. Basically system benefits increase with  $p$  as long as it is not sufficient to initiate a queue on the alternate route, but system benefits become independent of  $p$  once it exceeds  $p_c$  and both bottlenecks become busy. This result is illustrated in Figure 4.19 when there is a transition from NQ2-Case-II to Q2-Case-II; in Figure 4.20 where there is a transition from NQ1-Case-II to Q1-Case-II, and in Figure 4.21 where there is a transition from NQ1-Case-III to Q1-Case-III.

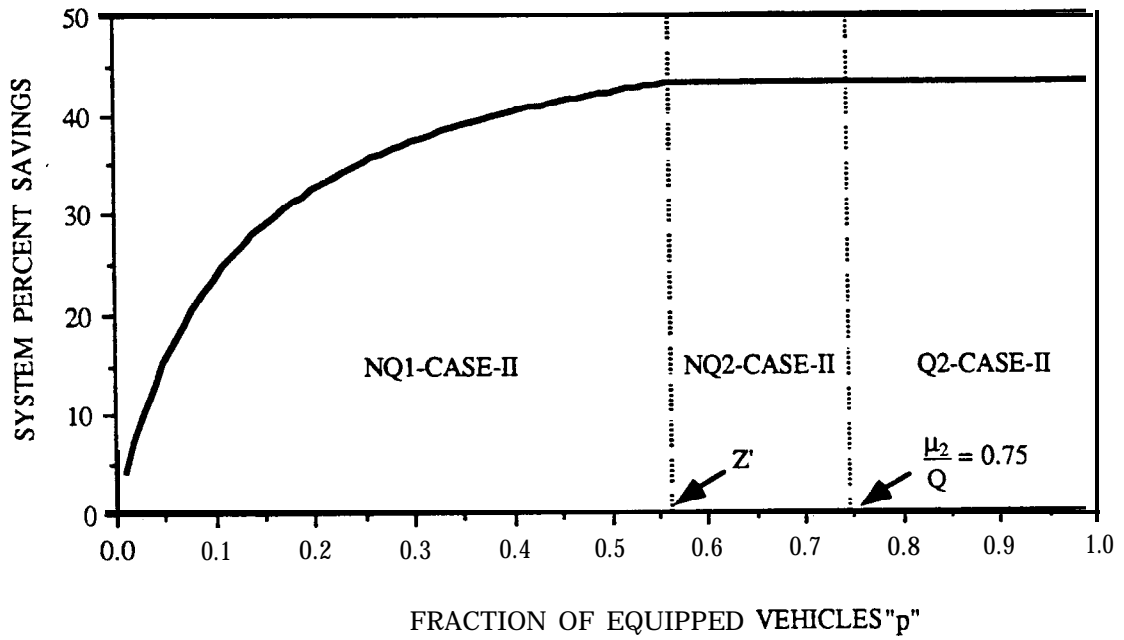


FIGURE 4.19 SYSTEM BENEFITS VERSUS "p"  
(NQ1-CASE-II, NQ2-CASEII, AND Q2-CASE-II)

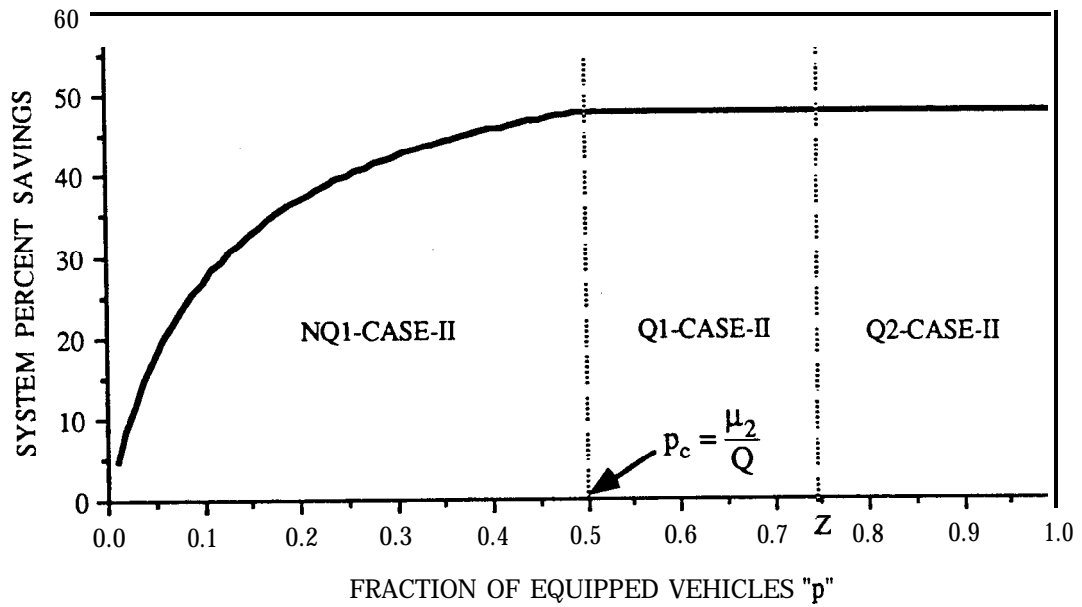


FIGURE 4.20 SYSTEM BENEFITS VERSUS "p"  
(NQ1-CASE-II, Q1-CASE-II, AND Q2-CASE-III)

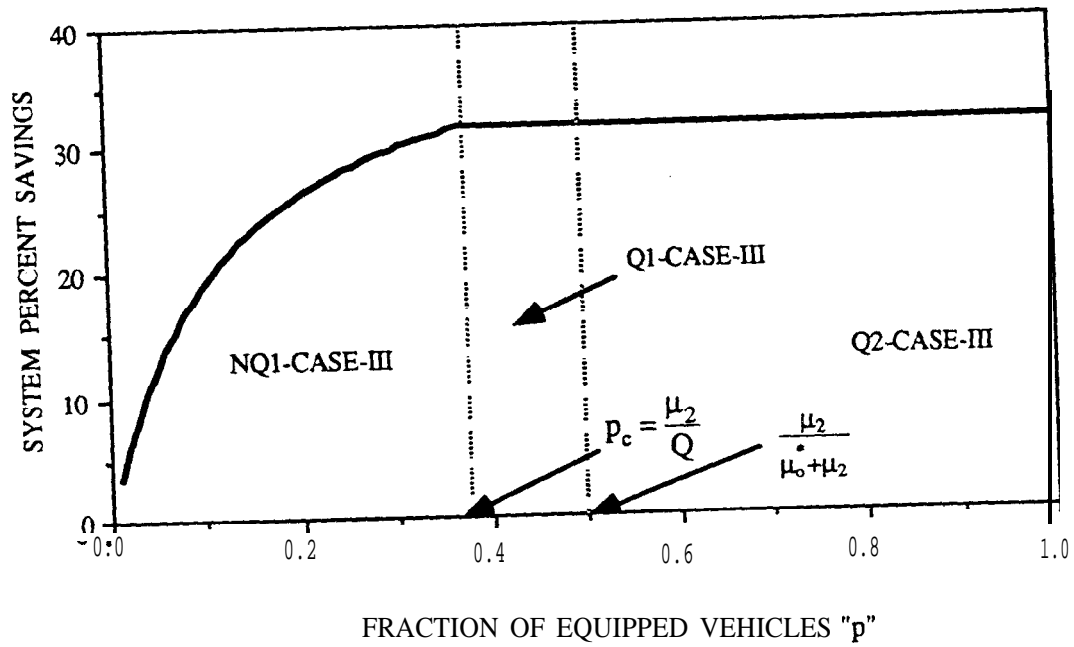


FIGURE 4.21 SYSTEM BENEFITS VERSUS "p"  
(NQ1-CASE-III, Q1-CASE-III, AND Q2-CASE-III)

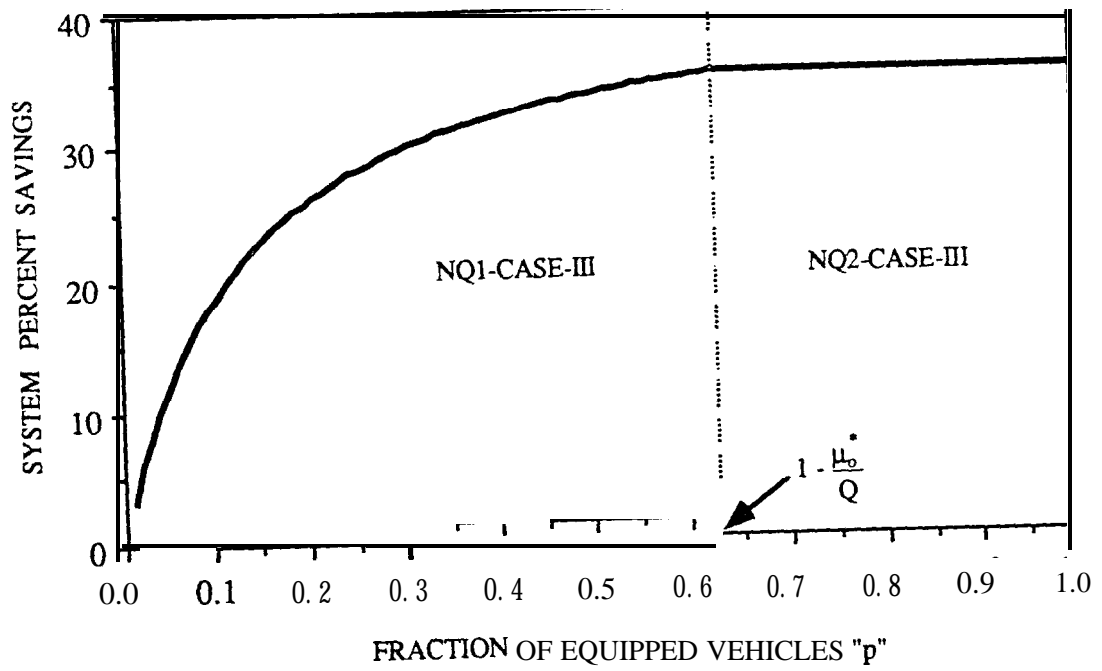


FIGURE 4.22 SYSTEM BENEFITS VERSUS "p"  
(NQ1-CASE-III AND NQ2-CASE-III)

2. When only the 'incident bottleneck is busy, system benefits increase with  $p$  as long as it is less than  $z$ ', the threshold value at which equilibrium occurs. The system benefits become independent of  $p$  and stay at a constant level once  $p$  exceeds  $z$ '. **This** result is shown in Figure 4.19 when there is a transition from NQ1-Case-II to NQ2-Case-II and 'in Figure 4.22 when there is a transition from NQ1-Case-III to NQ2-Case-III.
3. If  $p$  is large enough such that diverted traffic is sufficient to initiate a queue on the alternate route, equilibrium will be achieved sooner or later. Apparently it makes no difference for system benefits whether equilibrium is achieved earlier or not. This result applies to Q-type cases as shown in Figure 4.20 where there is a transition from Q1-Case-II to Q2-Case-II and in Figure 4.21 where there is a transition from Q1-Case-III to Q2-Case-III.

The findings imply that if the system management has the choice, then there is no need to equip more than  $p_c$  of the vehicles with ATIS, where  $p_c$  is the critical fraction of vehicles which initiates a queue on the alternate route. Hence, a strategy can be applied where no more than  $p_c$  is diverted to the alternate route. Under this strategy, benefits to the system and to the ATIS equipped travellers are maximized simultaneously. However, if more than  $p_c$  are equipped with ATIS, then this strategy might be inequitable for those who are equipped but not diverted. In a sense this is a limitation of the ATIS technology!

### 4.3 Sensitivity Analysis of The system Benefits

In this section we present the results of sensitivity analysis of system benefits to parameters other than  $p$ , using various numerical examples. Figure 4.23 illustrates that the following parameters influence the system benefits :

- the fraction of vehicles equipped with ATIS
- incident parameters: duration, severity, and location
- travel demand in the corridor

- corridor capacity: capacity of the freeway and capacity of the alternate route
- difference between free flow travel times on the two routes

It is clear that system benefits increase with the incident duration  $T$ . However, the increase is nonlinear and exhibits diminishing returns as shown in Figure 4.24. Since NQ-Case-1 is valid for incidents with short durations, the benefits are more sensitive to  $T$  in this case than in NQ1-Case-II. It is also clear that there are no benefits, i.e. information is irrelevant, when the incident duration is small (less than 15 minutes in this numerical example).

System benefits increase nonlinearly with incident severity, expressed as the reduction in the freeway capacity. ATIS becomes irrelevant for incidents with capacity reduction below 40% as shown in Figure 4.25. The iso-benefit contours shown in Figure 4.26 illustrate the sensitivity of the maximum system benefits (i.e.,  $p=p_c$ ) to the incident duration and severity. When the severity is high (above 60%) and the duration is small (less than one hour) the benefits are more sensitive to the duration than to the reduction in capacity. Similarly, when the reduction in capacity is low (say, less than 40%) and the duration is large (more than one and a half hours) the benefits are more sensitive to the reduction in capacity than they are to the incident duration. Generally, the sensitivity of the benefits to both parameters diminishes when both are very large.

As is to be expected, the further the incident location is from point A, the smaller the benefits are. This is shown in Figure 4.27. In other words, the further point C is from point A, the more traffic there is in between which cannot make use of information. The iso-benefit contours shown in Figure 4.28 illustrate the sensitivity of system benefits to the capacities of the two routes normalized by demand. The value of ATIS declines as the freeway capacity is improved. Incident management using ATIS is an alternative to expensive capacity improvement projects for freeways. On the other hand, improving the



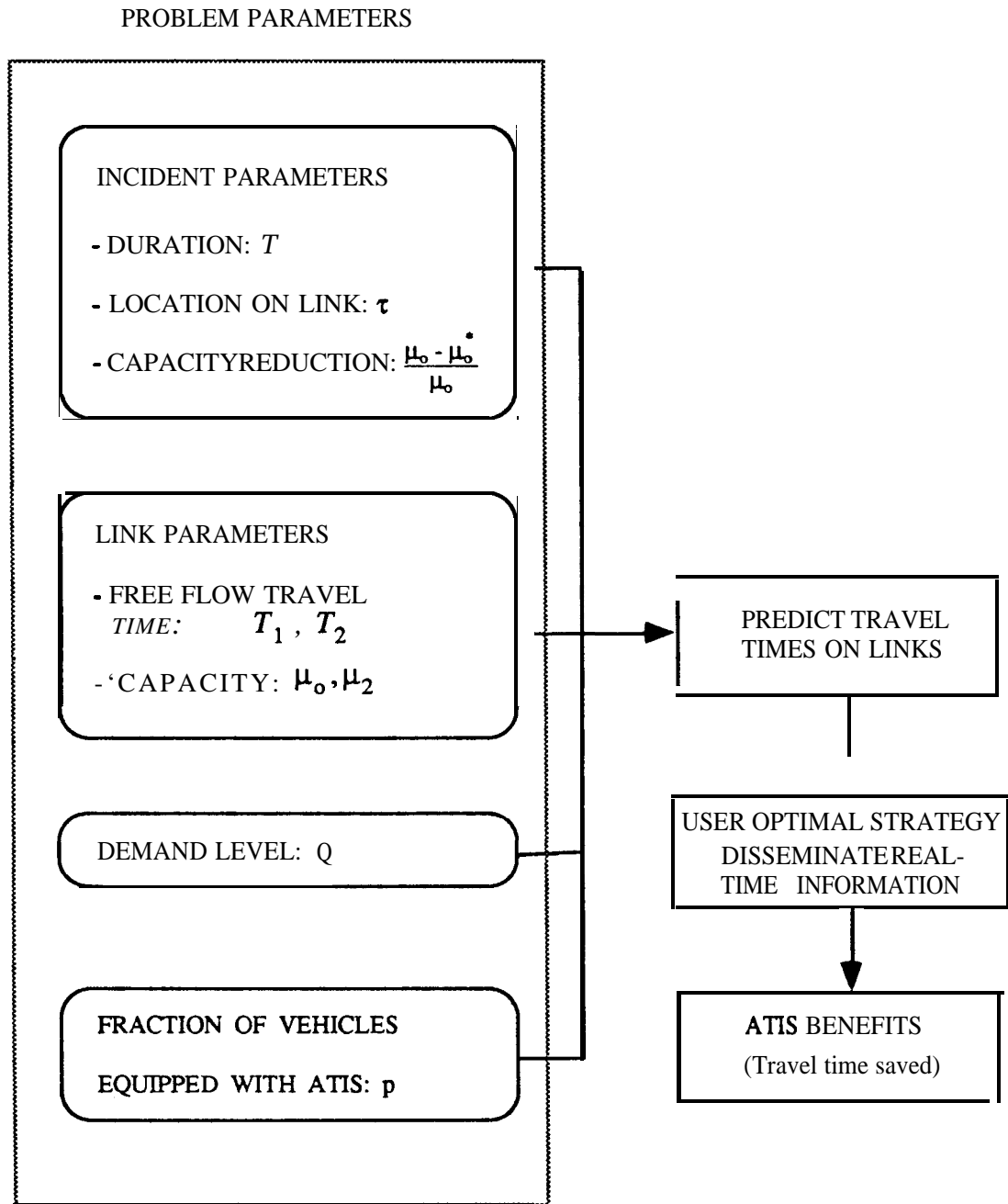


FIGURE 4.23 PARAMETERS USED IN THE EVALUATION OF ATIS BENEFITS

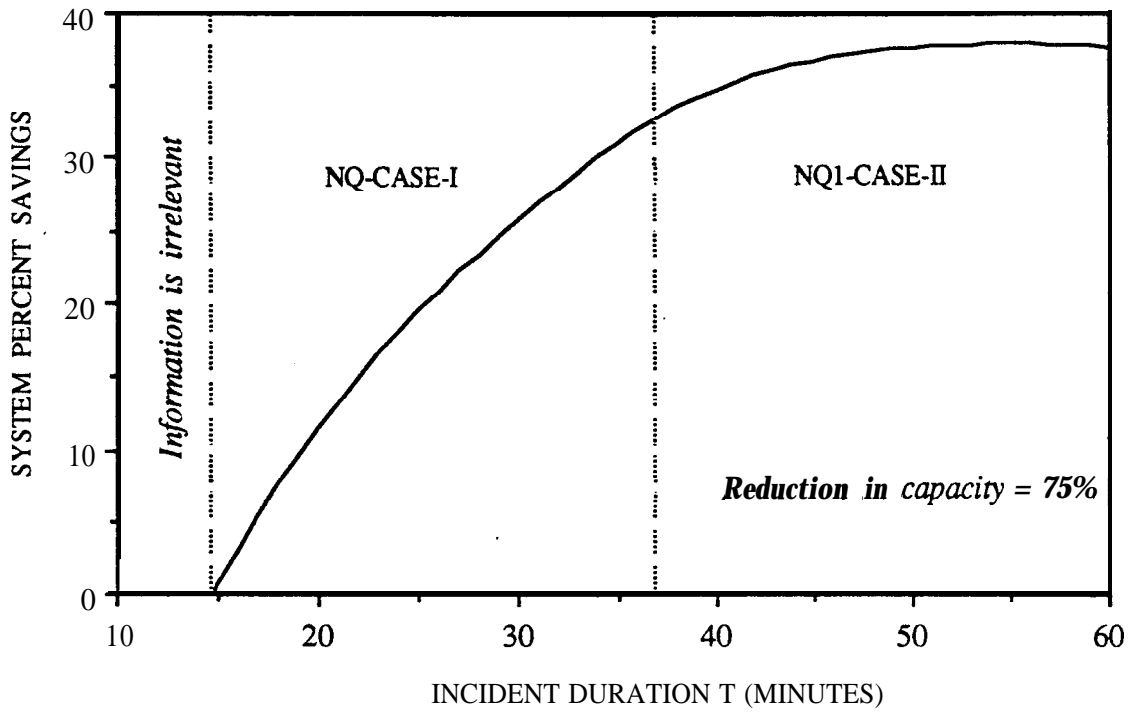


FIGURE 4.24 SENSITIVITY OF SYSTEM BENEFITS TO THE INCIDENT DURATION (T)

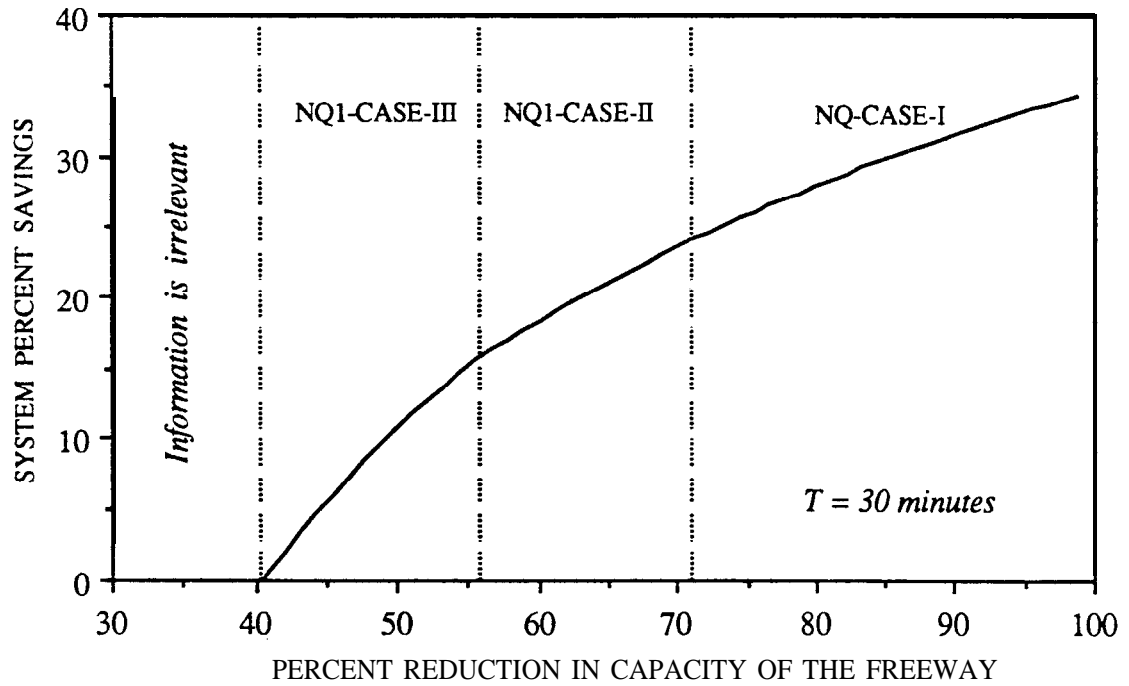


FIGURE 4.25 SENSITIVITY OF SYSTEM BENEFITS TO REDUCTION IN CAPACITY OF THE FREEWAY

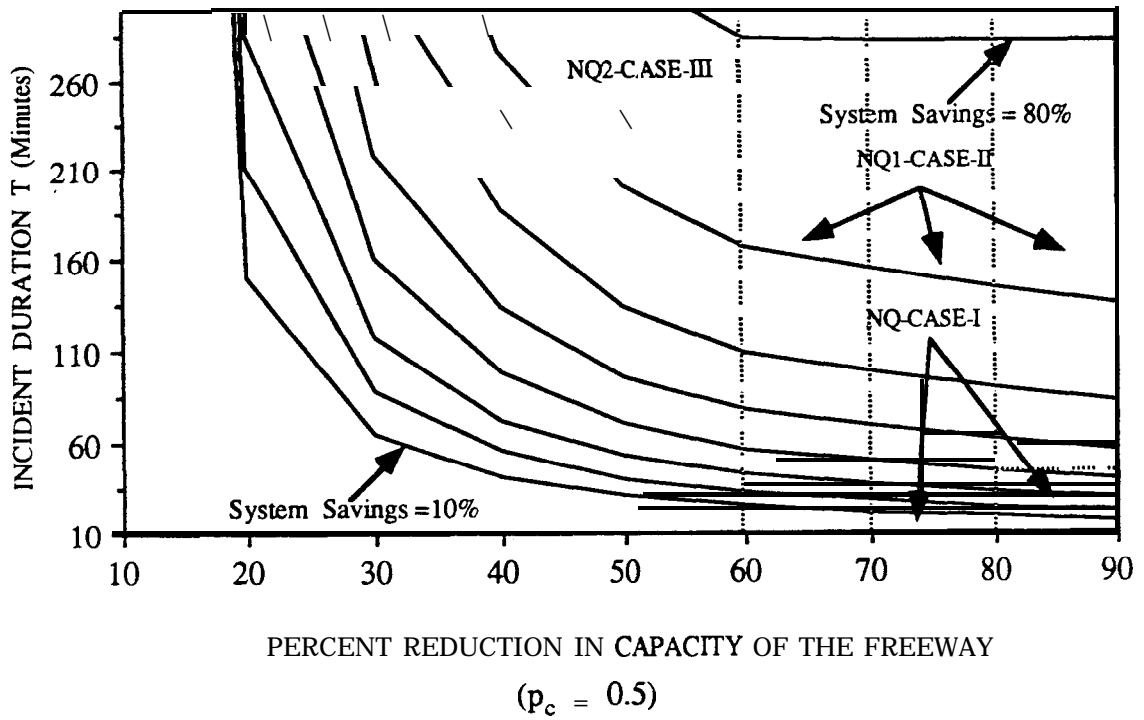


FIGURE 4.26 ISO-BENEFIT CONTOURS - INCIDENT SEVERITY AND DURATION-

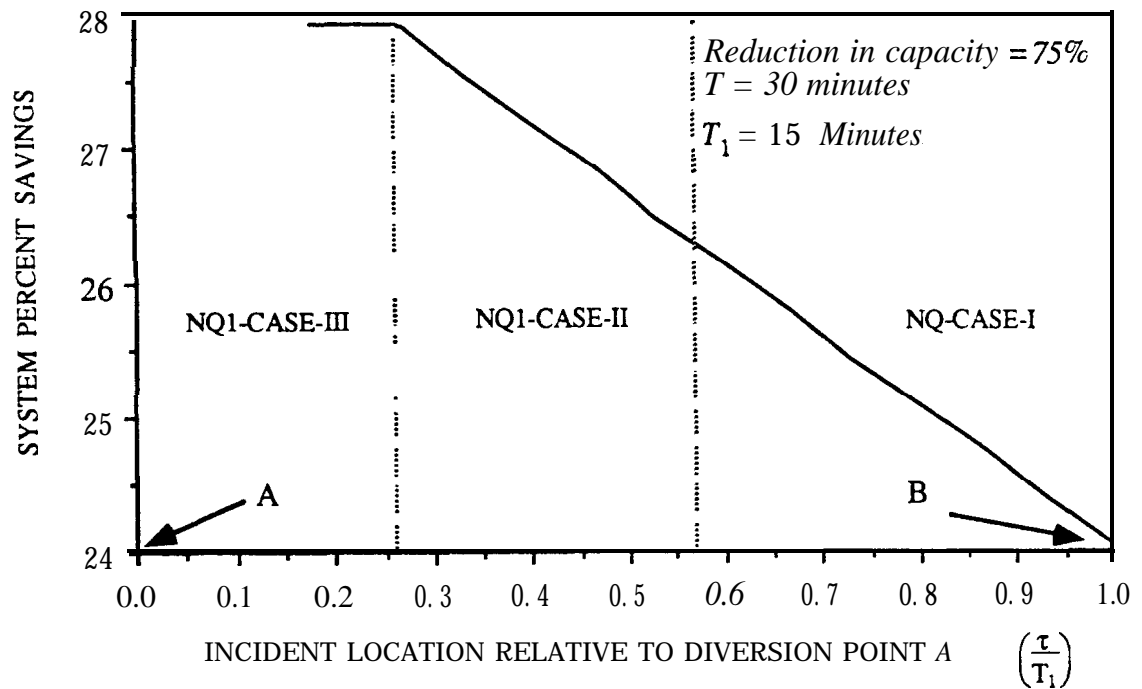


FIGURE 4.27 SENSITIVITY OF SYSTEM BENEFITS TO THE INCIDENT LOCATION

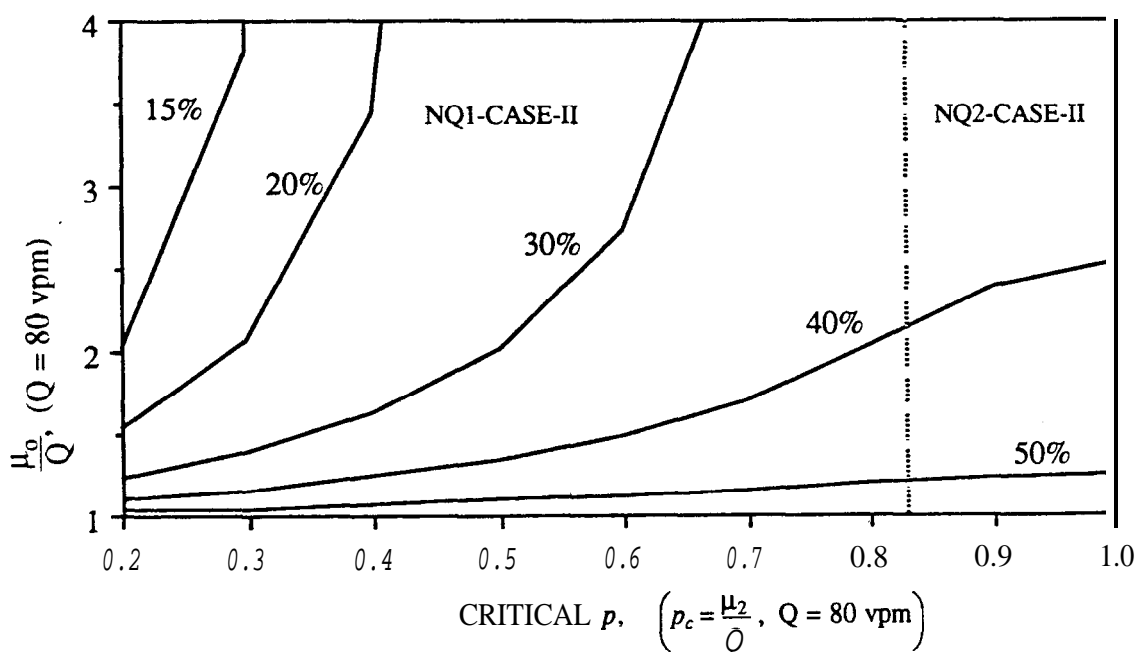


FIGURE 4.28 ISO-BENEFIT CONTOURS -IMPROVEMENT IN ROUTE CAPACITIES -

capacity of the alternate route enhances the role of **ATIS** in incident management. Therefore, it may be said that **ATIS** is an alternative to expensive capacity improvement projects for freeways, but not to overall corridor capacity enhancement. The increase in corridor demand means a larger incident queue on the freeway and therefore an increase in potential savings from **ATIS** as shown in Figure 4.29. There is a certain level of demand below which there is no system gain of **ATIS**.

Finally, we look at sensitivity of the benefits to the difference between free flow travel times on the two routes,  $T^*$ , as shown in Fig. 4.30. There is an upper limit of  $T^*$  which defines the relevance of **ATIS** information. When the alternate route is very long it is as if it does not exist. When  $T^*$  decreases, diversion continues for a longer period of time and consequently diverted as well as undiverted traffic have a better chance to save time. Therefore the system benefits are expected to increase as  $T^*$  decreases and are maximized when the two routes are identical.

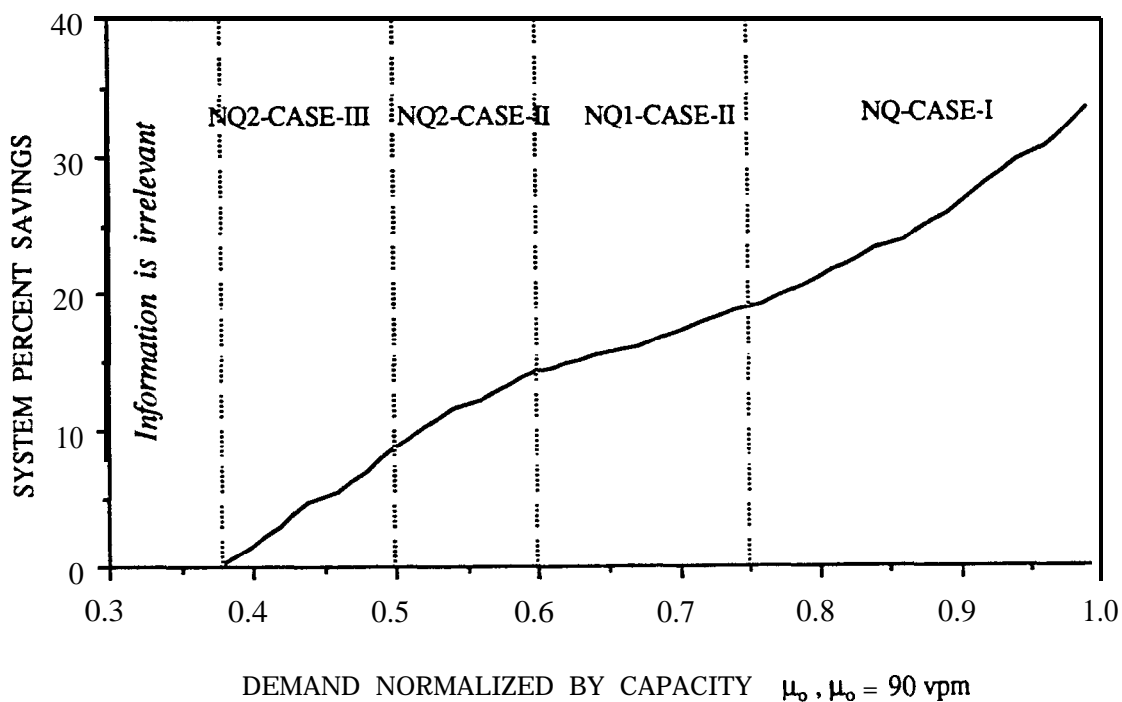
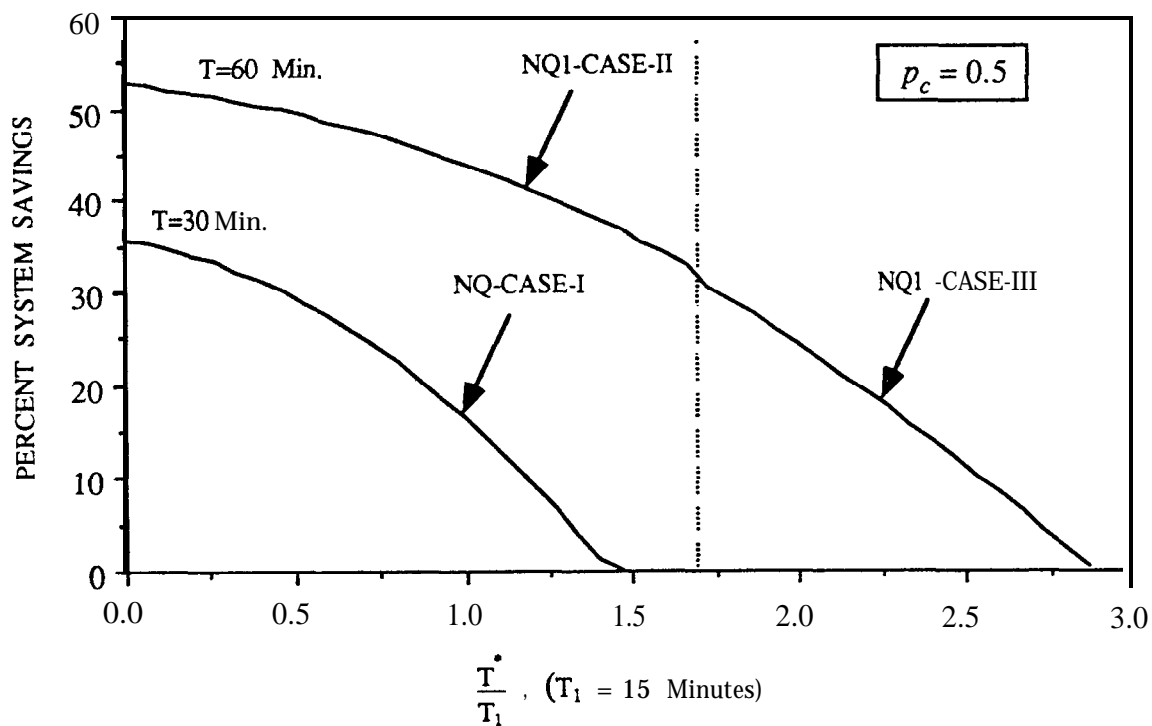


FIGURE 4.29 SENSITIVITY OF SYSTEM BENEFITS TO CORRIDOR DEMAND

FIGURE 4.30 SENSITIVITY OF SYSTEM BENEFITS TO  $T^*$

### On the Magnitude of ATIS Benefits

Using real life incident data we estimate the limits of system and user benefits of ATIS. We consider a corridor scenario that is likely to result in the maximum benefits of ATIS, herein after called the best corridor scenario. In this scenario, the corridor parameters are set as follows: system benefits increase with the demand  $Q$ , therefore we set  $Q$  to be close to but not exceeding the capacity of Route 1 (which is 90 vpm), say  $Q=89$  vpm, thus the off-peak conditions still hold. Also since the benefits are maximized at  $p_c$ , we set  $p_c=100\%$ , i.e a queue will not form on the alternate route even if all traffic is guided with ATIS. This is possible if the capacity of the alternate route is large enough to absorb all the corridor demand without having a queue, i.e if  $\mu_2=Q$ . The benefits increase when  $T^*$  decreases, hence we set  $T^*$  to be very small, say 0.01 minutes. Next, we consider some real life data of combinations of incident duration and severity as shown in Table 4.1. Recker et. al (1988) analyzed data about truck-involved freeway accidents that occurred on twenty-two freeway routes in Los Angeles, Ventura, and Orange Counties in California over a period of two years (1983-1984). The accident database includes 9508 such accidents involving trucks larger than pickups or panel trucks. A random sample of 332 of these accidents was obtained from the larger database and accidents were categorized according to the number of freeway lanes closed as shown in Table 4.1. The mean incident duration as well as the percentage of all truck accidents for each category were evaluated. Lindley (1986) presented empirical data that relates reduction in freeway capacity to the number of freeway lanes closed. We use his empirical findings to estimate reduction in the capacity of Route 1 (the freeway). System benefits are calculated for two extreme incident locations on Route 1: near points A and B. Note that the benefits are almost insensitive to the incident location for the given incident and corridor conditions. Although system benefits can be as high as 82% this applies only for 4.8% of all truck accidents. Category I (accidents with closure of one freeway lane) is the category with the most frequent

INCIDENT CATEGORY	INCIDENT DESCRIPTION	MEAN INCIDENT DURATION (Minutes)	% OF ALL TRUCK ACCIDENTS	APPROXIMATE % CAPACITY REDUCTION *	INCIDENT LOCATION $\tau$ (Minutes)	ATIS SYSTEM BENEFITS	
I	ONE LANE CLOSED	60	35%	50%	1	49.59%	≈ 50%
					15	49.47%	
II	TWO LANES CLOSED	110	14.8%	80%	1	74.66%	≈ 75%
					15	74.57%	
III	ALL LANES CLOSED	140	4.8%	100%	1	82.37%	≈ 82%
					15	82.18%	
IV-1	- NO LANES CLOSED - NO INJURIES	50	31%	30%	1	32.44%	≈ 32%
					15	32.33%	
IV-2	- NO LANES CLOSED - INJURIES	75	14.4%	40%	1	49.40%	≈ 49%
					15	49.35%	

\* Estimation of the capacity reduction is based on the empirical results reported by Lindley (1986).

TABLE 4.1 ATIS SYSTEM BENEFITS FOR TRUCK RELATED ACCIDENTS  
Source of incident statistics: Recker et. al (1988)

accidents and system benefits are 50% for this category. System benefits weighed over all categories are:

$$(0.35)(50\%) + (0.148)(75\%) + (0.048)(82\%) + (0.31)(32\%) + (0.144)(49\%) = 50\%.$$

Thus, the expected upper limit of system benefits for truck-involved accidents is 50%.

Minimum and maximum values of user benefits are estimated depending on the time of arrival to point A. The results are shown in Table 4.2. Category I results in user benefits of 35%-64%. Similarly, user benefits are weighed over all categories and the expected upper limit of user benefits for truck-related accidents is in the range of 36%-63%.

So far we have looked only at truck-related accidents. The **vast majority** of all incidents, however, are non-truck related, they are vehicle disablements (Giuliano 1989). Truck-related accidents are expected to be less than 5% of all incidents. Giuliano (1989) analyzed incident data for a 12 mile section of the Santa Monica freeway (I-10) in Los Angeles. She found that 80% of the non-truck incidents do not result in any lane blockages, see Table 4.3. This is obviously related to the availability of shoulders in the case study area. Despite that no lane blockage occurs in these incidents, capacity is reduced by the impact of gawkers block which is estimated to be on the order of 25% (Lari et. al, 1982; Goolsby and Smith, 1971). The expected upper limit of system benefits for non-truck incidents weighed over all categories is estimated from Table 4.3 and is equal to 26%. Using Table 4.4, the upper limit of user benefits for non-truck incidents is estimated to be in the range of 17%-36%.

Hence, system benefits weighed over truck and non-truck incidents are:

$$(0.05) (50\%) + (0.95) (26\%) = 27\%$$

and the range of user benefits weighed over truck and non-truck incidents is:

$$\text{Minimum : } (0.05) (36\%) + (0.95) (17\%) = 18\%$$

$$\text{Maximum : } (0.05) (63\%) + (0.95) (36\%) = 37\%$$



INCIDENT CATEGORY	INCIDENT DESCRIPTION	MEAN INCIDENT DURATION (Minutes)	% OF ALL TRUCK ACCIDENTS	APPROXIMATE % CAPACITY REDUCTION *	RANGE OF USER BENEFITS (Minimum - Maximum)
I	ONE LANE CLOSED	60	35%	50%	35% - 64%
II	TWO LANES CLOSED	110	14.8%	80%	71% - 84%
III	ALL LANES CLOSED	140	4.8%	100%	90.2% - 90.3%
IV-1	- NO LANES CLOSED - NO INJURIES	50	31%	30%	16% - 46%
IV-2	- NO LANES CLOSED - INJURIES	75	14.4%	40%	26% - 64%

\* Estimation of the capacity reduction is based on the empirical results reported by Lindley (1986).

TABLE 4.2 RANGE OF USER BENEFITS FOR TRUCK RELATED ACCIDENTS  
Source of incident statistics: Recker et. al (1988)

INCIDENT CATEGORY	INCIDENT DESCRIPTION	MEAN INCIDENT DURATION (Minutes)	% OF ALL NON-TRUCK INCIDENTS	APPROXIMATE % CAPACITY REDUCTION	ATIS SYSTEM BENEFITS
I	ONE LANE CLOSED	60	18%	50%*	50%
II	TWO LANES CLOSED	100	2%	80%*	73%
III	NO LANES CLOSED	30	80%	25% **	19%

\* Estimation of the capacity reduction is based on the empirical results reported by Lindley (1986).

\*\* The average impact of gawkers block is 25% reduction in capacity, Lari et. al (1982)

TABLE 4.3 ATIS SYSTEM BENEFITS FOR NON-TRUCK INCIDENTS  
Source of incident statistics: Giuliano (1989)

INCIDENT CATEGORY	INCIDENT DESCRIPTION	MEAN INCIDENT DURATION (Minutes)	% OF ALL NON-TRUCK INCIDENTS	APPROXIMATE % CAPACITY REDUCTION	RANGE OF USER BENEFITS (Minimum - Maximum)
I	ONE LANE CLOSED	60	18%	50%*	35% - 64%
II	TWO LANES CLOSED	100	2%	80%*	70% - 83%
III	NO LANES CLOSED	30	80%	25%**	12% - 28%

\* Estimation of the capacity reduction is based on the **empirical** results reported by Lindley (1986).

\*\* The average impact of gawkers block is 25% reduction in capacity, Lari et. **al** (1982)

TABLE 4.4 RANGE OF USER BENEFITS FOR NON-TRUCK INCIDENTS  
Source of incident statistics: Giuliano (1989)

Therefore, the **range** of user benefits is 18% - 37%.

The lower limit of **ATIS** user and system benefits is obviously zero, it occurs when information is irrelevant because the initial delay is less than  $T^*$ . This applies to the best corridor scenario mentioned earlier when:

- 1) 'there is a very minor loss of capacity of the incident section such that demand will be less than the remaining capacity. This is likely to occur in many of the shoulder disablements where the capacity is reduced by only 1% (Lindley, 1986).
- 2) the incident duration is less than the time needed to reach its location **from** point A, i.e when  $T < \tau$ . Since  $0 < \tau < T_I$  by definition and  $T_I = 15$  minutes, then **ATIS** will be useful for all incidents with durations larger than 15 minutes but **ATIS** may or may not be useful for incidents with durations less than 15 minutes.

It is important to remember that the above estimates of the user and system benefits apply for the best corridor scenario, i.e the capacity of the alternate route is sufficient to absorb the corridor demand, the free flow travel times on Routes 1 and 2 are similar, and all traffic is guided with **ATIS**. Furthermore, the estimates are based on several assumptions: **ATIS** equipped travellers follow instructions to divert to the alternate routes and **ATIS** system can predict the incident duration accurately and send it to guided traffic without any lag of information. In the next chapter we look at the possible consequences of the relaxation of these assumptions.

#### 4.4 Summary of User and System Benefits

The results of user and system benefits of **ATIS** are represented by the three dimensional Figure 4.31. The left side plane is a dynamic profile of the user benefits: it tracks percent time savings on a real time basis. The different levels of market penetration are represented by the parallel left side planes. If these planes are overlaid on top of each

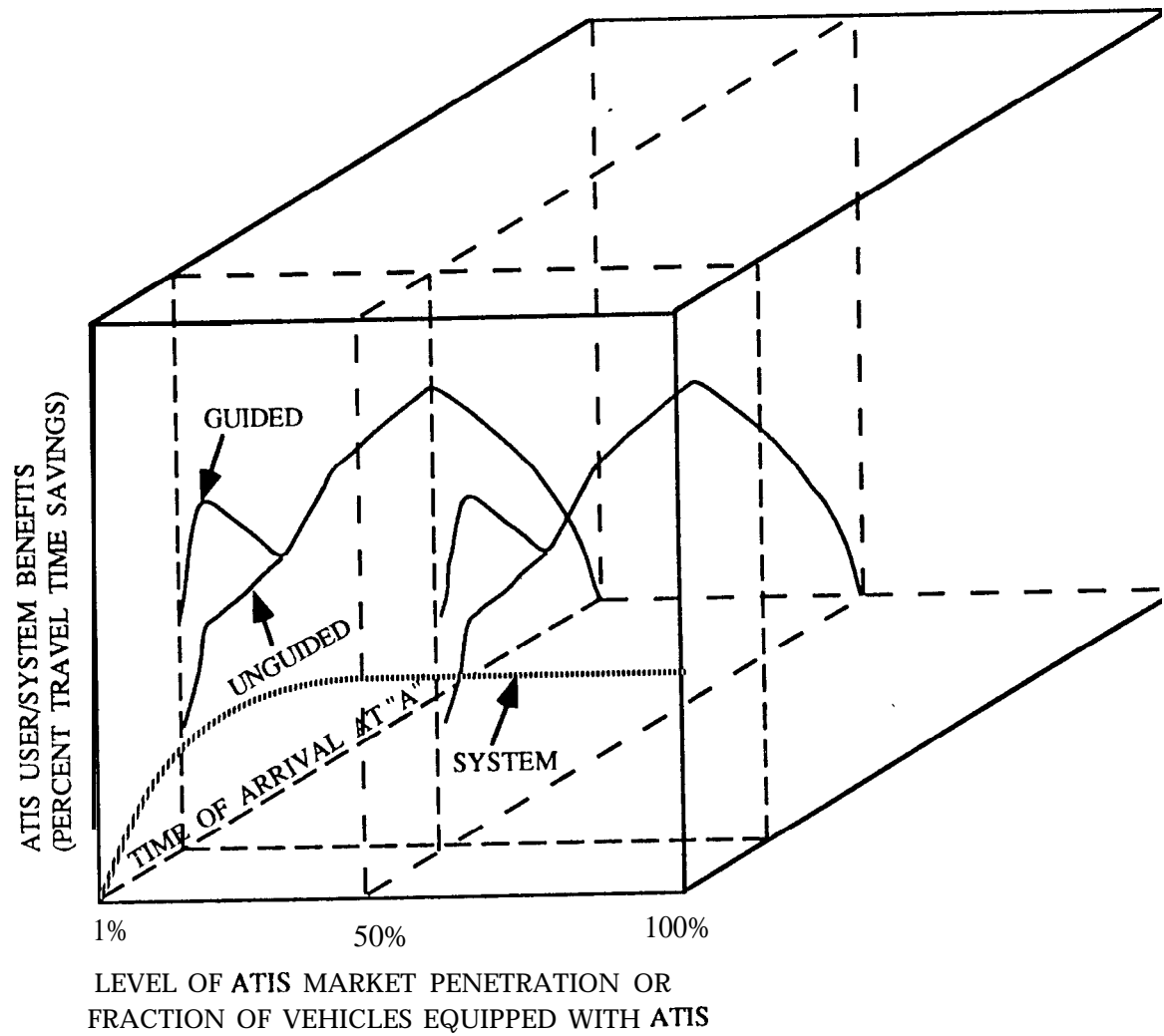


FIGURE 4.31 MODELLING USER AND SYSTEM BENEFITS OF ATIS UNDER INCIDENT CONDITIONS

other, the three dimensional figure is reduced into a two dimensional figure where the percent savings are plotted versus the time of arrival at point A.

System benefits for a certain level of market penetration (the fraction of vehicles equipped with **ATIS**) are found by integrating travel time savings to guided and unguided traffic over time. This integration reduces the three dimensional Figure 4.31 into a two dimensional figure as shown by the front face which illustrates a sketch of system benefits plotted against the level of market penetration of **ATIS**.

Finally, it is clear that increasing the proportion of guided traffic improves equity by narrowing the gap in travel time savings between guided and unguided traffic and consequently equalizing the distribution of travel time savings among all system users. However, as the proportion of guided traffic increases, the advantage to guided traffic having **ATIS** and the disadvantage to unguided traffic not having **ATIS** decreases. This has a counter-effect on the incentive to have **ATIS**. Furthermore, system benefits saturate at a certain level of market penetration, chosen arbitrarily as 50% in Figure 4.31. This saturation reflects operational limitations of the highway facilities such as bottlenecks and the limited number and capacities of feasible alternate routes, as well as the lack of incentive for unequipped **travellers** to have route guidance information.

## 5. 'MODEL ENHANCEMENTS AND EXTENSIONS

In this Chapter we analyze practical strategies for incident management and relax some of the assumptions made in the preceding analysis. We also look into other applications and extensions of the model.

### 5.1 Diversion Correction and Pulsed Diversion

So far we have assumed that vehicles with **ATIS** will follow directions to divert to a shorter route whenever so instructed by the **ATIS**. This section explains consequences of relaxing this assumption from two perspectives: 1) that only some but not all **ATIS** vehicles divert when so instructed, or 2) that **ATIS** vehicles are provided with route travel time information instead of instructions to divert

To analyze the first assumption, we use the queueing diagram of Q-Case-I shown in Figure 3.9. A portion of this figure is reproduced in Figure 5.1. The dashed lines represent the expected cumulative count using each route if all **ATIS** vehicles follow instructions. In **reality**, it is possible that some **ATIS** vehicles may not follow instructions and would remain on Route 1 despite the fact that Route 2 is faster. If this is the case, then the solid lines represent a more realistic queueing diagram, and the subscript  $r$  is used to refer to this situation. Since the real diversion rate,  $p_r Q$ , is less than the assumed one,  $pQ$ , the time needed to reach equilibrium increases from  $K$  to  $K_r$ . As mentioned earlier, once equilibrium is reached, the diversion rate should be reduced to  $p'Q$ . Later on, at time  $t_r$ , however, it is found that the actual diversion rate is less than  $p'Q$ . To correct this situation, the diversion rate is increased to the maximum possible,  $pQ$ , so as to match the equilibrium rate,  $p'Q$ . Once equilibrium is reached again at time  $t_e$ , there is no need to divert more than  $p'Q$ . However, if the rate  $p'Q$  is diverted, the picture repeats itself until Route 1 becomes ultimately faster and diversion ends. It is noted that when some **ATIS** vehicles do not follow instructions to divert, diversion takes longer because of fluctuation

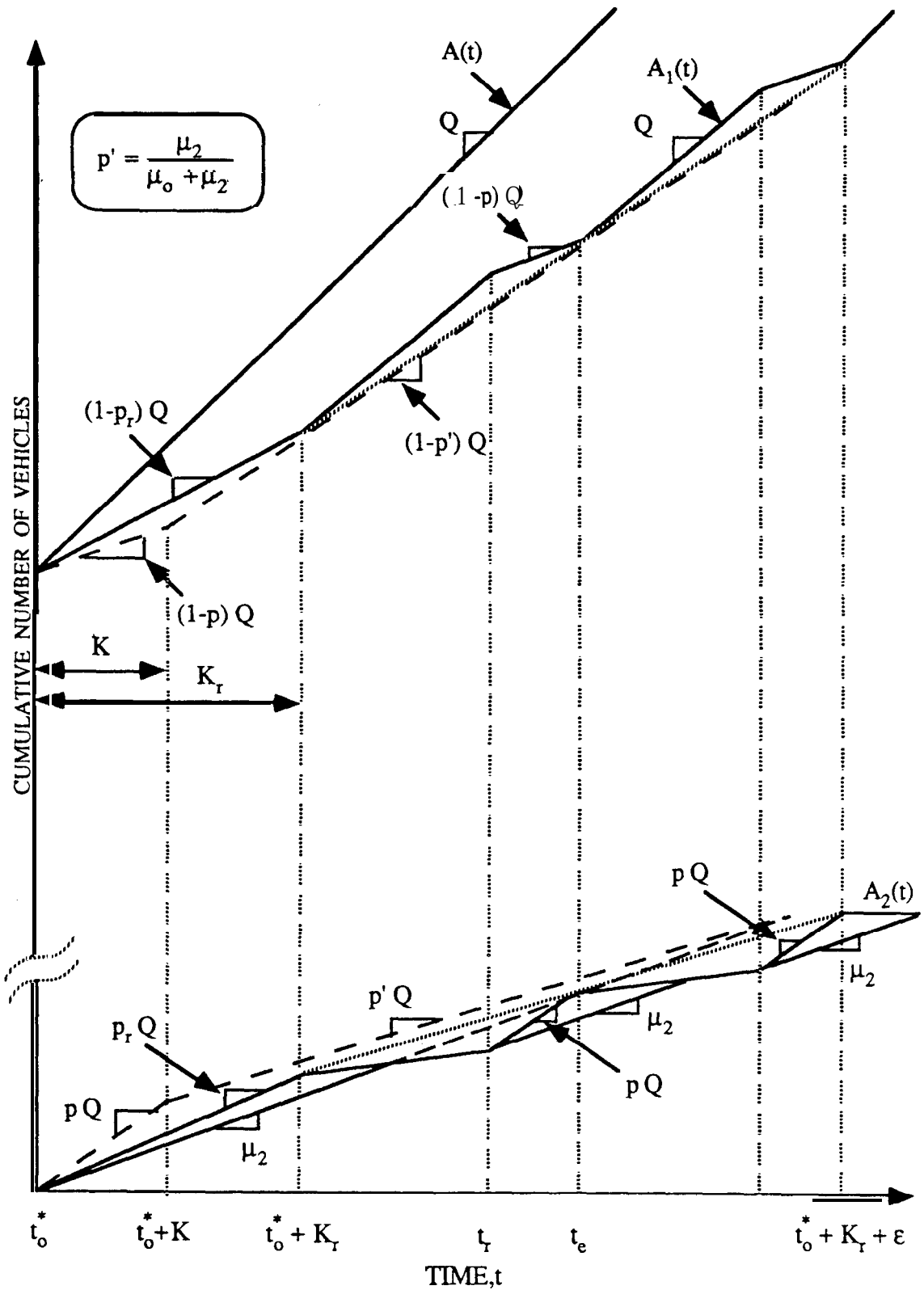


FIGURE 5.1 DIVERSION CORRECTION



in the diversion rate with an average value that is less than  $p'Q$ . *Of course*, this will reduce system efficiency.

If the response of guided traffic to diversion instructions is low, equilibrium may never be achieved even with  $p=1$ . Thus, in the cases of queue evolution discussed earlier, lower values of  $p$  insufficient to achieve **equilibrium**, are equivalent to lower response from the **travellers** to route guidance.

An alternative to providing **ATIS** vehicles with instructions to divert is to give them route travel time information. If the diversion criterion of **ATIS** travellers is to choose the route with the minimum travel time, then the queue evolves as in Figure 5.2. All **ATIS** vehicles divert for a time period of  $K$  starting from the moment the incident occurs, and stop diverting when Route 2 becomes congested enough to deter them away. This occurs at time  $t_0^* + K + \epsilon_1$ , after which all **ATIS** vehicles use Route 1. This will cause Route 1 to become congested at time  $t_0^* + K + \epsilon_1 + \epsilon_2$  when **ATIS** vehicles shift back to Route 2 again. The process of pulsed diversion continues until travel time on Route 1 **reverts** to being less than that on Route 2, approximately at time  $t_0^* + K + \epsilon$ , where

$$\epsilon = \sum_{i=1}^{i=6} \epsilon_i$$

The average rate of diversion to Route 2 during this process is comparable to  $p'Q$ .

It is expected that there will be some time lag needed by **ATIS** to update information. The influence of this time lag on diversion is of concern at times when the diversion rate has to be changed (increased or decreased). This influence can easily be analyzed using queueing diagrams that are similar to those shown in Figures 5.1 and 5.2.

Analysis of the pulsed diversion is necessary in real life situations where accuracy is of concern. In Chapter 3 we approximated the pulsed diversion curves, shown in both Figures 5.1 and 5.2, by a straight line with an average slope that is comparable to  $p'Q$ .

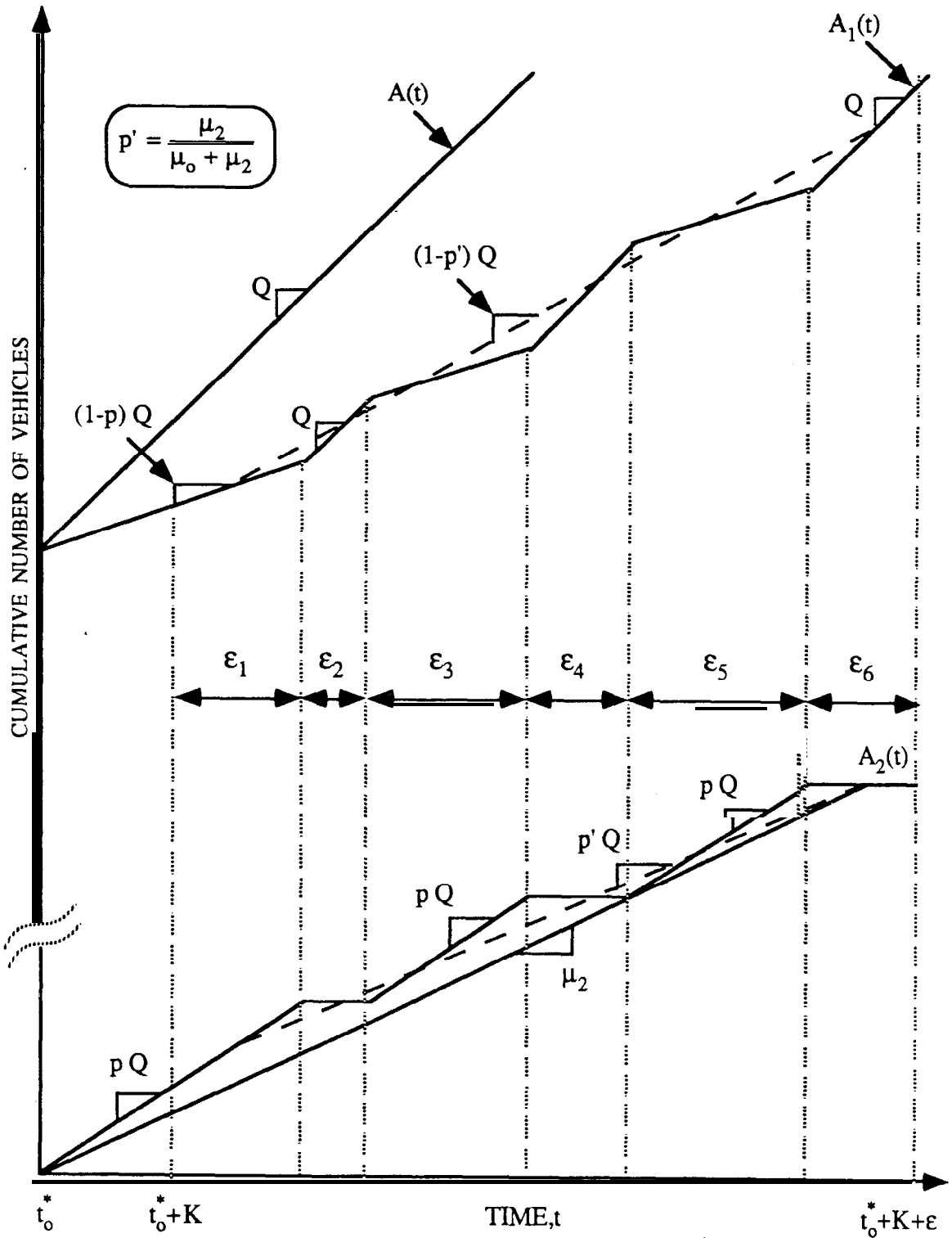


FIGURE 5.2 PULSED DIVERSION

This approximation is an alternative to analyzing queue evolutions in full detail. Nonetheless, the main effects of **ATIS** on queue evolutions could still be realized.

## 5.2 Underestimation and Overestimation of the Incident Duration

The incident duration is one of the most important factors in determining which case of queue evolution results. Models have been developed to estimate the duration of an incident as a function of a few variables, such as the number of the freeway lanes blocked by the incident (**Recker** et. al, 1988). In real life, however, it is unlikely to find two incidents with identical conditions. That makes it very difficult to predict accurately the incident duration  $T$ . In this section we analyze possible consequences and remedies of the misprediction (underestimation or overestimation) of  $T$ . To illustrate this, an example is used where the initial estimate of  $T$  is such that NQ-Case-I results.

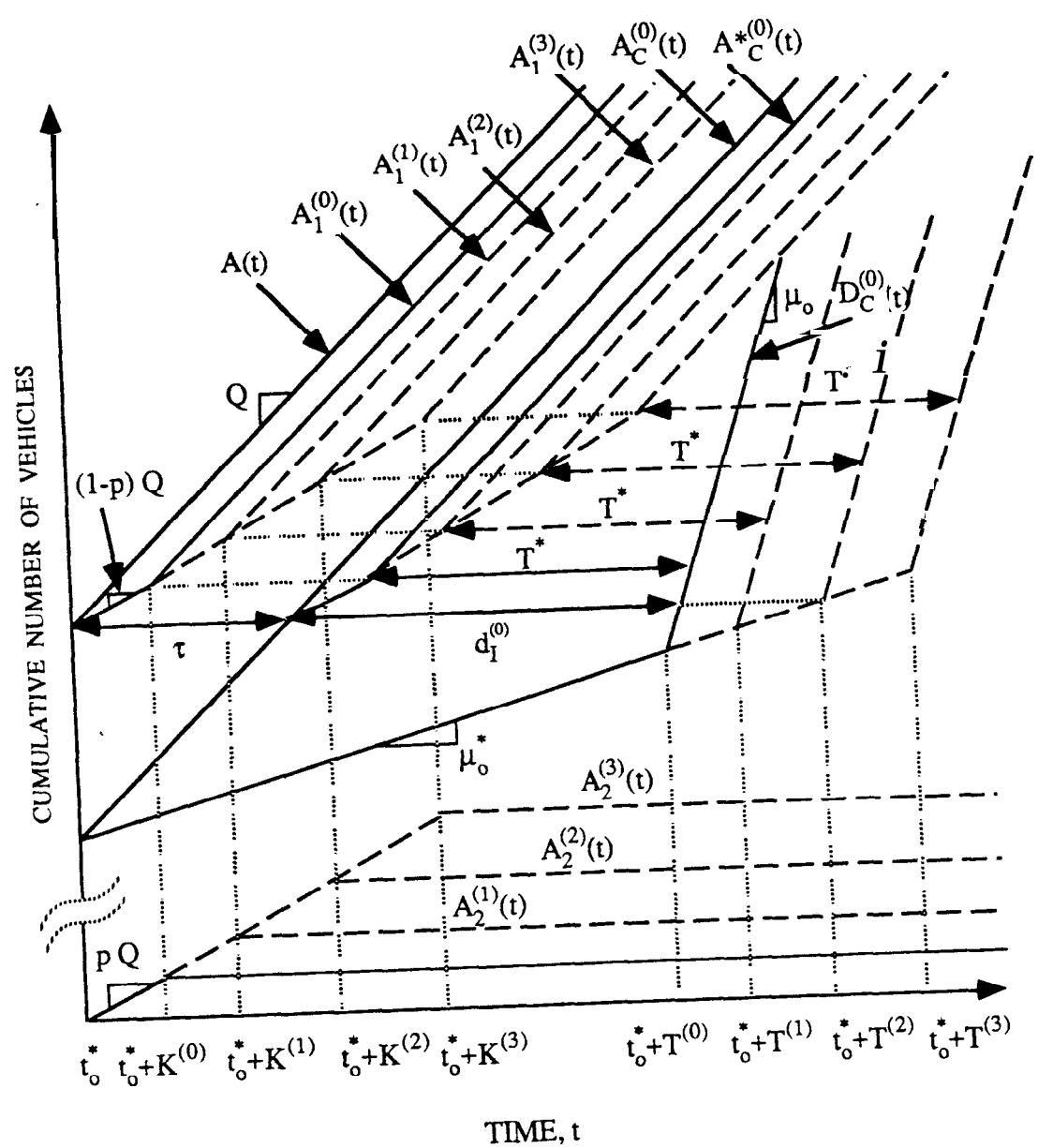
### Underestimation of $T$

The initial estimate of  $T$  is referred to as  $T^{(0)}$ . If

$$T^{(0)} < \tau \left( \frac{Q}{\mu_o^*} \right) ,$$

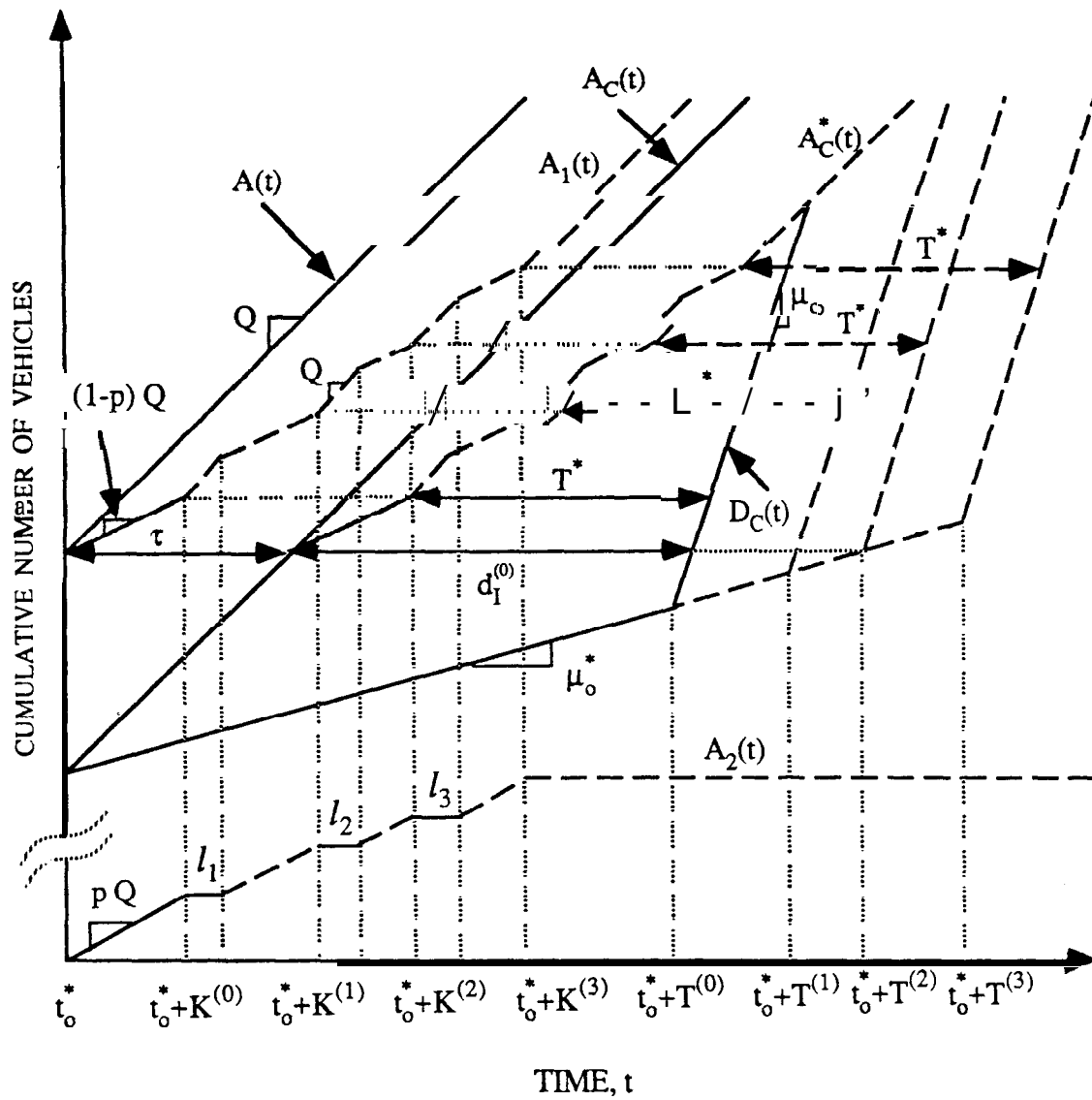
then NQ-Case-I results, as shown by the queueing curves with solid lines in Figures 5.3 - 5.5. The value of  $T$  is updated in the **ATIS** system through feedback from the progress of the incident clearance process. The figures depict several updates of the incident duration  $T$ :  $T^{(1)}$ ,  $T^{(2)}$ , and  $T^{(3)}$ . Consequently the queue evolution and the diversion of **ATIS** vehicles can be revised based on the updated values of  $T$ , as shown by the dashed lines in Figures 5.3 - 5.5. In all of these figures,  $T$  has been underestimated.

The initial estimate of  $K$ , the duration of diversion, is based on  $T^{(0)}$ . If  $T$  is updated before the initial diversion duration  $K^{(0)}$  ends, then the decision will be to extend the



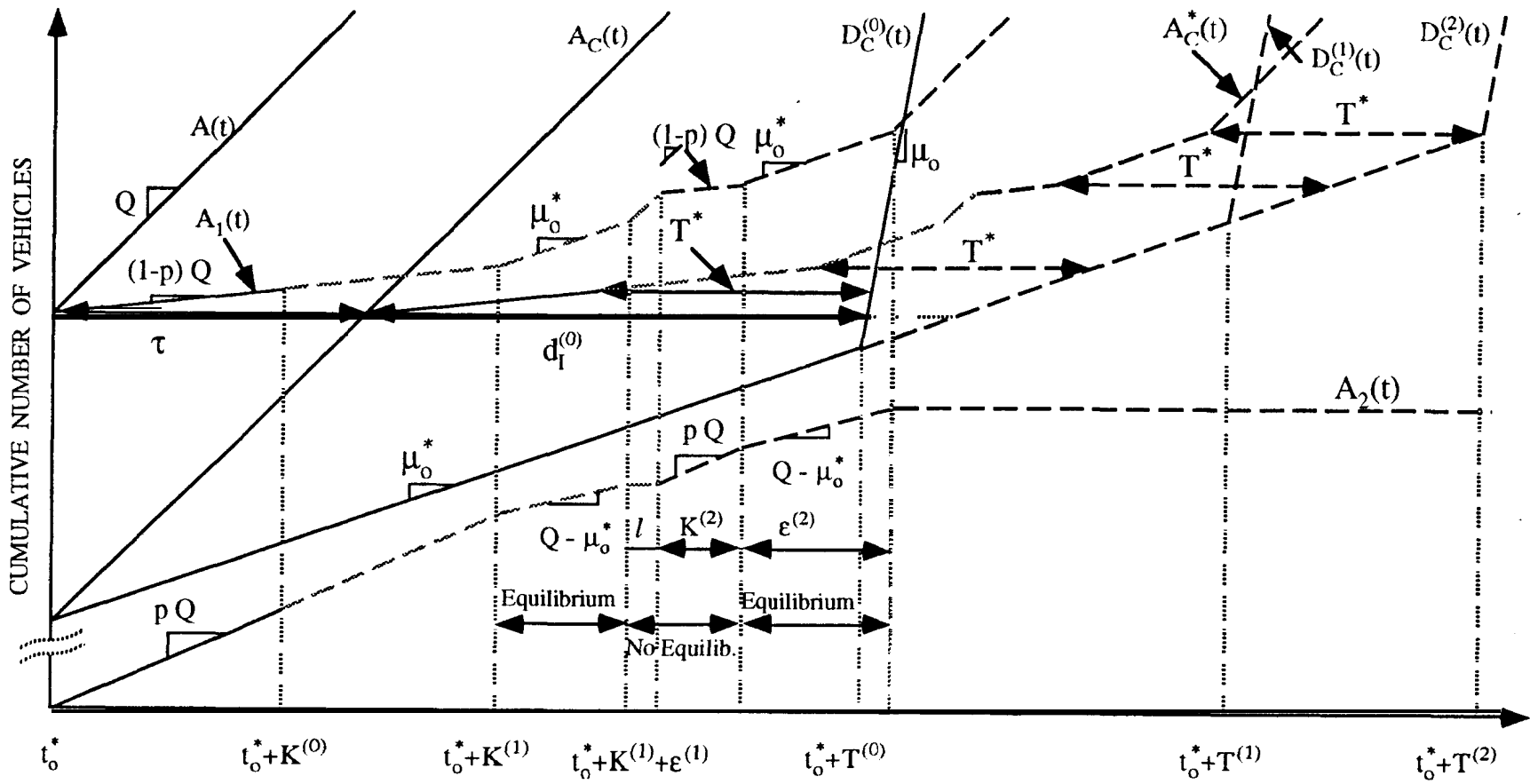
$$d_1^{(i)} > T^* \text{ and } p < z', \quad z' = \frac{T \left( 1 - \frac{\mu_o^*}{Q} \right) \cdot T^*}{T - \tau - T^*}$$

FIGURE 5.3 UNDERESTIMATION OF THE INCIDENT DURATION AND EARLY REVISION OF DIVERSION (NQ-CASE-I AND NQ1-CASE-II)



$$d_I^{(i)} > T^* \text{ and } p < z', z' = \frac{T \left( 1 - \frac{\mu_o^*}{Q} \right) - T^*}{T - \tau - T^*}$$

FIGURE 5.4 UNDERESTIMATION OF THE INCIDENT DURATION AND LATE REVISION OF DIVERSION (NQ-CASE-I AND NQ1-CASE-II)



$$d_1^{(i)} > T^* \text{ and } p > z', \quad z' = \frac{T \left( 1 - \frac{\mu_0^*}{Q} \right) - T^*}{T - \tau - T^*}$$

FIGURE 5.5 UNDERESTIMATION OF THE INCIDENT DURATION WITH A MIXTURE OF EARLY AND LATE REVISIONS OF DIVERSION (NQ-CASE-I AND NQ2-CASE-II)

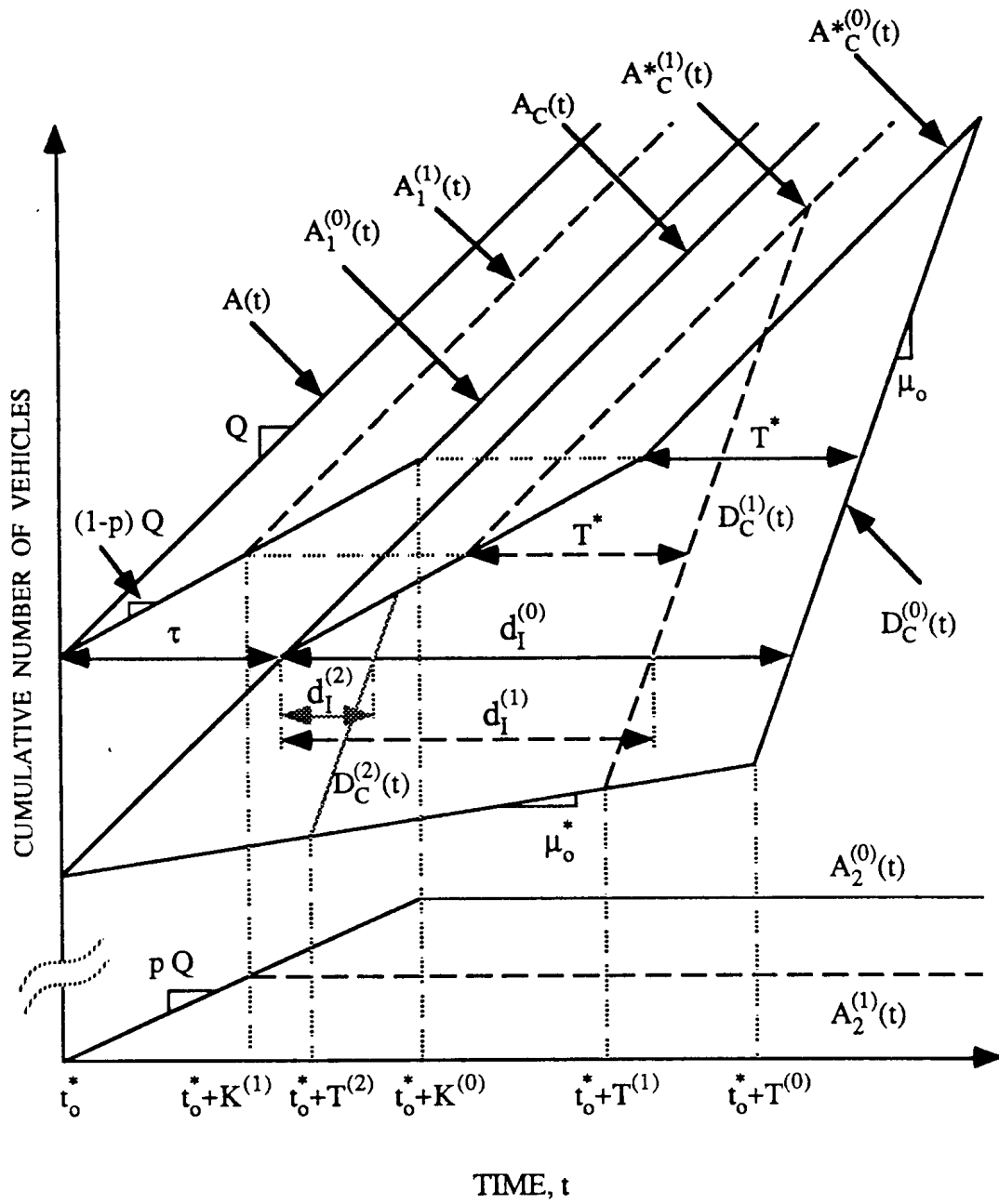
diversion time by  $K^{(1)}-K^{(0)}$ , where  $K^{(1)}$  is the first revised value of  $K$ . As long as  $T$  is updated and  $K$  is revised before the diversion ends, the queue will evolve as in Figure 5.3. But if the updated  $T$  is revised after a decision to stop diversion has been made, then the queue will evolve as in Figure 5.4, which shows pulsed diversion. The **ATIS** equipped travellers are deprived of the benefits of diversion and system efficiency decreases for time durations:  $l_1, l_2$ , and  $l_3$ . Note that in both Figures 5.3 and 5.4 a shift from NQ-Case-I to NQ1-Case-II occurs when  $T$  is updated for the third time, i.e., when  $T=T^{(3)}$ , where

$$T^{(3)} > \tau \left( \frac{Q}{\mu_o^*} \right),$$

Note also that in both figures equilibrium is never achieved because the fraction of vehicles equipped with **ATIS** is less than  $z'$ , the minimum fraction needed to initiate equilibrium. In Figure 5.5 this fraction is larger than  $z'$  and equilibrium is achieved for a period of time  $\epsilon^{(1)}$ , equilibrium is interrupted for a period of time  $l+K^{(2)}$ , and it is established again for a period of time  $\epsilon^{(2)}$ . This figure shows a mixture of early and late revisions of diversion. Finally, it is evident that if the diversion occurs when  $T$  is underestimated, any value of the revised delay  $d_1^{(i)}$ , where  $i=1,2,3$ , will be larger than  $T^*$  and travellers guided with **ATIS** will always gain by being diverted to Route 2.

### Overestimation of $T$

Figure 5.6 illustrates the queueing diagram for NQ-Case-I with  $T$  being overestimated. There are two scenarios for the revised delay  $d_1^{(i)}$ , either: (1)  $d_1^{(i)} > T^*$ ; or (2)  $d_1^{(i)} < T^*$ . The first scenario is represented by the dashed lines in Figure 5.6 while the second scenario is represented by the grey lines. In the second scenario, **ATIS** is irrelevant and no equipped vehicles should be diverted to Route 2. Unfortunately there is some time interval during which diversion will occur before  $T$  can be revised and a decision to stop



$$d_I^{(0)}, d_I^{(1)} > T^*, \text{ but } d_I^{(2)} < T^*$$

FIGURE 5.6 OVERESTIMATION OF THE INCIDENT DURATION AND POSSIBLE REVISION OF THE DIVERSION DURATION (NQ-CASE-I)



diversion can be taken. During this time interval, **ATIS** equipped travellers will be disadvantaged by **travelling** on the longer route. The same observation also occurs in the first scenario (except when  $T$  is updated and  $K$  is revised during the time interval  $[t_o^*, t_o^* + K^{(I)}]$ ). The only way to prevent **ATIS** equipped travellers from being disadvantaged is **not** to overestimate  $T$ . On the other hand, underestimation of  $T$  will not make equipped travellers worse off than if they have not been equipped with **ATIS**. Therefore, to be on the safe side, it is better from the perspective of guided traffic to underestimate the incident duration than to overestimate it. From a system perspective it is better to minimize the magnitude of the prediction error in  $T$  *regardless* of whether this error is positive or negative.

### 5.3 The Queue Spillback and the Queue Backup Problems

It was assumed in the idealized corridor that the queue on the alternate route does not spill'back to the freeway. Also it was assumed that the incident queue does not reach upstream of point A. This section deals with the consequences of the relaxation of these two assumptions.

#### Queue Spillback

The queue of diverted vehicles may spill back to the freeway. Figure 5.7 illustrates that the queue on Route 2 reaches point A on the freeway at time  $t_s$ . The queue spillback to the freeway can be controlled by reducing the diversion rate from  $pQ$  to  $\mu_2$ , the capacity of the alternate route. Note that equilibrium starts at time  $t_{e1}$  when there is no spillback, but is delayed until  $t_{e2}$  when there is. When no more than  $\mu_2$  is diverted, the queueing delay on Route 2 is reduced (as shown by the light shaded area) and the queueing delay on the freeway is increased (as shown by the dark shaded area). The net queueing delay is usually positive except when the fraction of **ATIS** equipped vehicles is very large. The disadvantage of this is a loss in system efficiency and in benefits to equipped travellers.

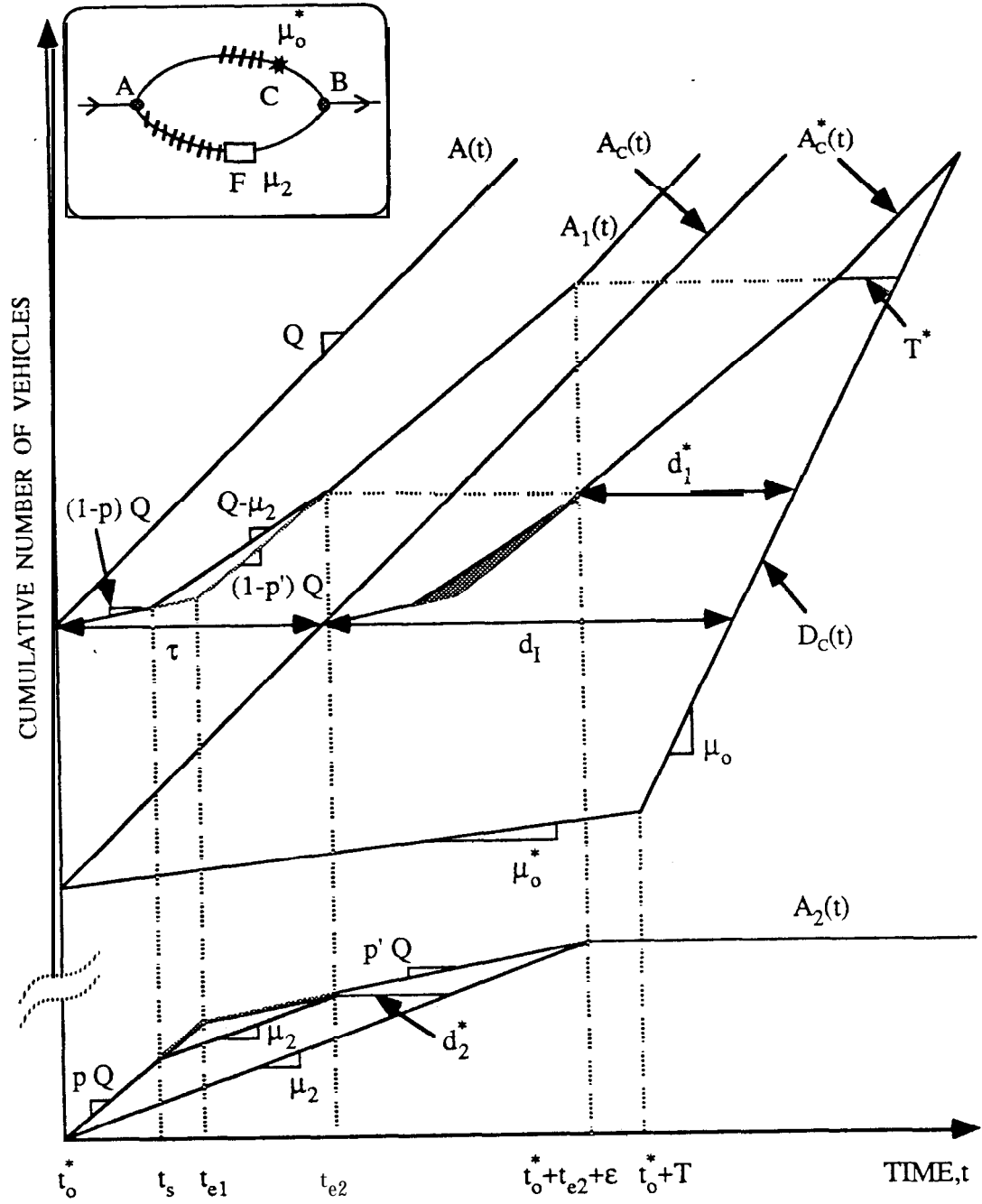


FIGURE 5.7 CONTROL OF THE QUEUE SPILLBACK USING ATIS (Q-CASE-I)

The best solution for the spillback problem is not to let it occur. This may be achieved if the **ATIS** equipped vehicles are diverted to several alternate routes.

### Queue Backup

The incident queue may back on the freeway upstream of point A therefore causing delay to guided traffic which wishes to exit at that point. It is expected that with **ATIS** the backup problem will be delayed and possibly eliminated. Figure 5.8 illustrates a case where without **ATIS** the queue reaches point A at time  $t_{s1}$  but at a later time  $t_{s2}$  with **ATIS**. The backup problem can be eliminated if the initial delay warrants immediate diversion and there is a sufficient number of **ATIS** vehicles to be diverted, i.e when:

$$d_I > T^* \text{ and } (1-p)Q < \mu_o^*$$

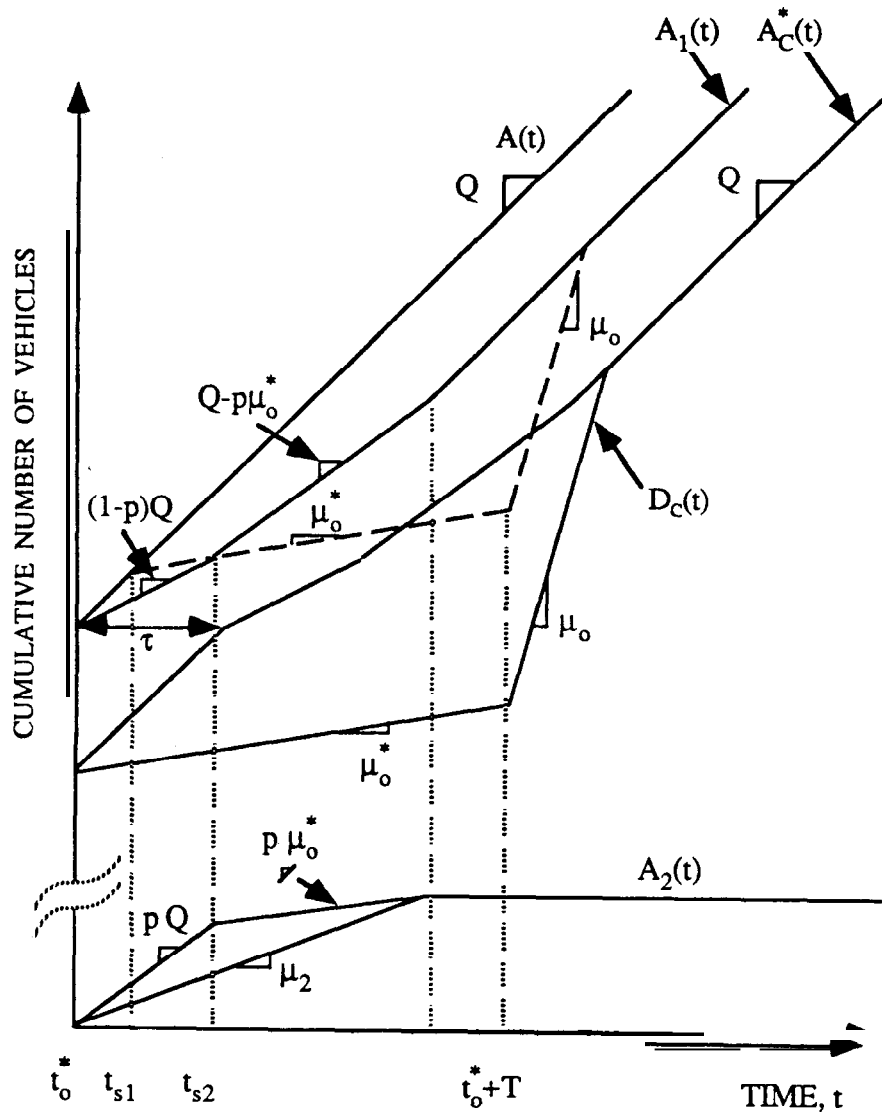
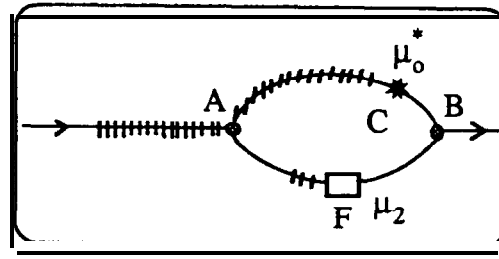
Thus, after time  $t_{s2}$ , the departure rate from point A to point C cannot exceed  $\mu_o^*$  until the incident is cleared. One would expect that the maximum rate that can be diverted becomes  $p\mu_o^*$  instead of  $pQ$ . Because of this restriction on the diversion rate, equilibrium may not be reached within time interval  $[t_o^*, t_{s2}]$ . Failure to reach equilibrium causes a loss in the system efficiency and in the benefits to **ATIS** equipped vehicles. These losses can be avoided, however, if **ATIS** vehicles are diverted at several alternate routes rather than only one route.

Hence, to avoid the problems of the queue spillback and the queue backup, **ATIS** vehicles should be diverted to several alternate routes (provided that they exist).

## 5.4 Study Extensions and Future Research

### Network Extension

A contribution of this study is that it has established the nuclei of a large scale simulation model. The idea is to develop the large scale model from a base of simple queueing methods such as the one used in this research. The model extension is relevant



$$(1-p) Q > \mu_0^*$$

FIGURE 5.8 QUEUE BACKS UPSTREAM OF POINT A (Q-CASE-I)

for applications to real life networks with multiple origins and destinations. Under incident conditions, traffic guided with **ATIS** is spread over a wider space through diversion to several alternate routes. The effectiveness of **ATIS** in spreading incident congestion over space is strongly correlated with the number and the excess capacity of the alternative routes. The alternative routes can be either adjacent freeways or major arterials usually parallel to the highway facility on which the incidents occur. When expanding the model it is also important to consider dynamic network effects that result from diversion such as the queue spillback to the freeway and the queue backup on the city streets.

The diversion of guided traffic to major arterials may increase the travel cost for travellers originally using these arterials. In addition to this, diversion may cause secondary queueing delay to the traffic moving on city streets perpendicular to the arterials. Consequently, the implementation of the user optimal strategy under such conditions may result serious equity problems to city **street** traffic. This stimulates the need to consider alternative network-wide strategies for dissemination of real time traffic information. Examples of these are the system optimal and the group optimal strategies which are discussed briefly below.

The objective of the system optimal strategy is to optimize the total travel cost for all trips in the network, whether made by **ATIS** equipped or unequipped vehicles. Real time traffic information is disseminated to influence travellers' decisions to use system optimal routes. The outcome of this strategy is very much influenced by the overall capacity of the alternative routes and also the types of cost included in the optimization. The travel cost **may** include the social cost of diversion to city streets such as the potential safety hazards, air and noise pollution, and the long term effects on land value...etc. The diverted traffic can be easily spread over a wider space if the network has alternate routes with fairly large capacities. In such a case, the increase in the social cost may not be significant. This is also true if incidents result short durations of traffic diversion (perhaps in the range of 20-30 minutes). Under such conditions, the optimization is likely to result more guided traffic

being diverted to the city streets than in the case of the user **optimal** strategy. In corridors with low capacity alternate routes, the social cost of diversion is likely to be high. Similarly, the social cost of diversion is relevant in extreme conditions where there is a high frequency of severe incidents such as truck related incidents resulting long durations of traffic diversion to city streets (perhaps in the order of hours). Under these conditions, the optimization is expected to result in more guided traffic remaining on the freeway. Obviously, this strategy is not in the *best* of interest to guided traffic. In fact, guided travellers may **find** themselves using the longer travel time routes, thus sacrificing for the sake of the public good.

The group optimal strategy is a special case of the system optimal strategy where the environment of optimization is the group of **ATIS** equipped vehicles. For example, in the corridor analyzed, instructions are transmitted to equipped travellers to use a route such that the total travel time for equipped travellers going from *A* to *B* is minimized. This strategy can be used to establish diversion priorities. For example, under incident conditions, High Occupancy Vehicles (**HOVs**) equipped with **ATIS** can be given the priority to divert to the shortest route (even if it does not have HOV lanes). This provides an additional incentive for commuters to switch to **HOVs** and therefore enhances the role of **HOVs** in reducing the overall network congestion. The group optimal strategy can also be used by the private sector such as express delivery services, taxi cabs, and the trucking industry. Those might be the early adopters of the **ATIS** technology. Under incident conditions, the priority of diversion to the shortest routes is given to vehicles loaded with valuable commodities or perishable goods.

The model network-wide extension is expected to be accomplished gradually. Figure 5.9 illustrates a preliminary step for the model extension: a corridor composed of a freeway and two parallel arterials. In the morning commute, trips are destined to the CBD, i.e. a many-to-one O-D table, while in the evening commute trips originate at the CBD and are distributed to various destinations. Guided traffic can be diverted to the parallel arterials

at several freeway exits. The next step will be to consider sample configurations or skeletons of real life networks with multiple 0-Ds such as the Bay area and the Los Angeles basin.

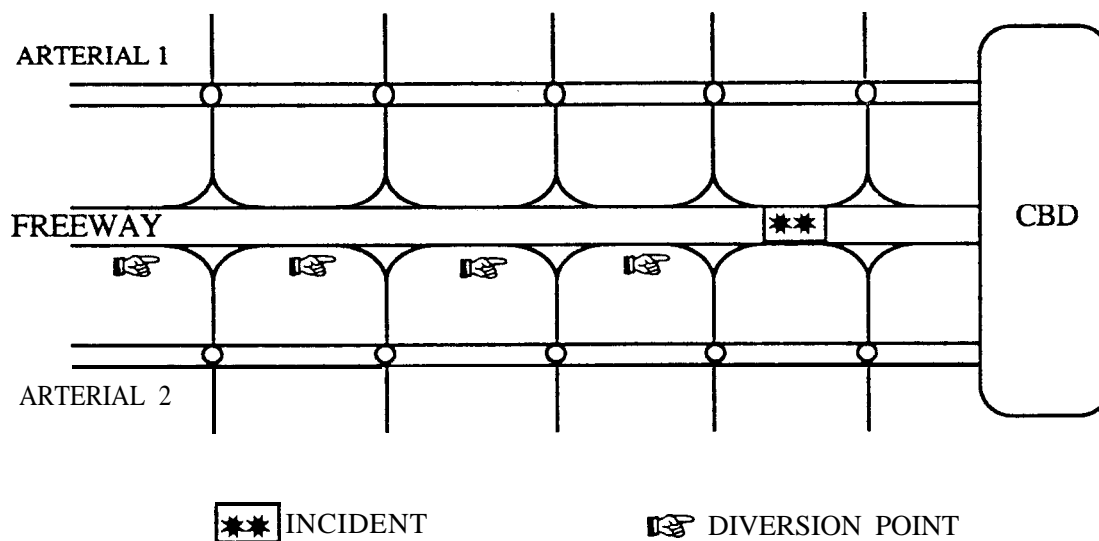


FIGURE 5.9 CORRIDOR UNDER INCIDENT CONDITIONS WITH ATIS (MULTI-DIVERSION POINTS)

### Peak Period Incidents

Another extension of this research is to analyze the peak-period incidents. The peak period is defined as the period during which the corridor demand exceeds the capacity of the freeway and is shown as time interval  $[t_o, t_f]$  in Figure 2.3.

In the absence of incidents, equilibrium is established in the corridor analyzed during the peak period. Equilibrium is achieved by the commuters choosing the shortest travel time routes on the basis of their daily experience. Queue evolution for the peak period equilibrium is shown in Figure 5.10. The curve  $A(t)$  shows the arrivals at **A** before traffic splits between the two routes.  $A_1(t)$  and  $A_2(t)$  represent respectively the arrivals to bottlenecks **E** on Route 1 and **F** on Route 2. All travellers use Route 1 until equilibrium is achieved at time  $t_e$ , that is

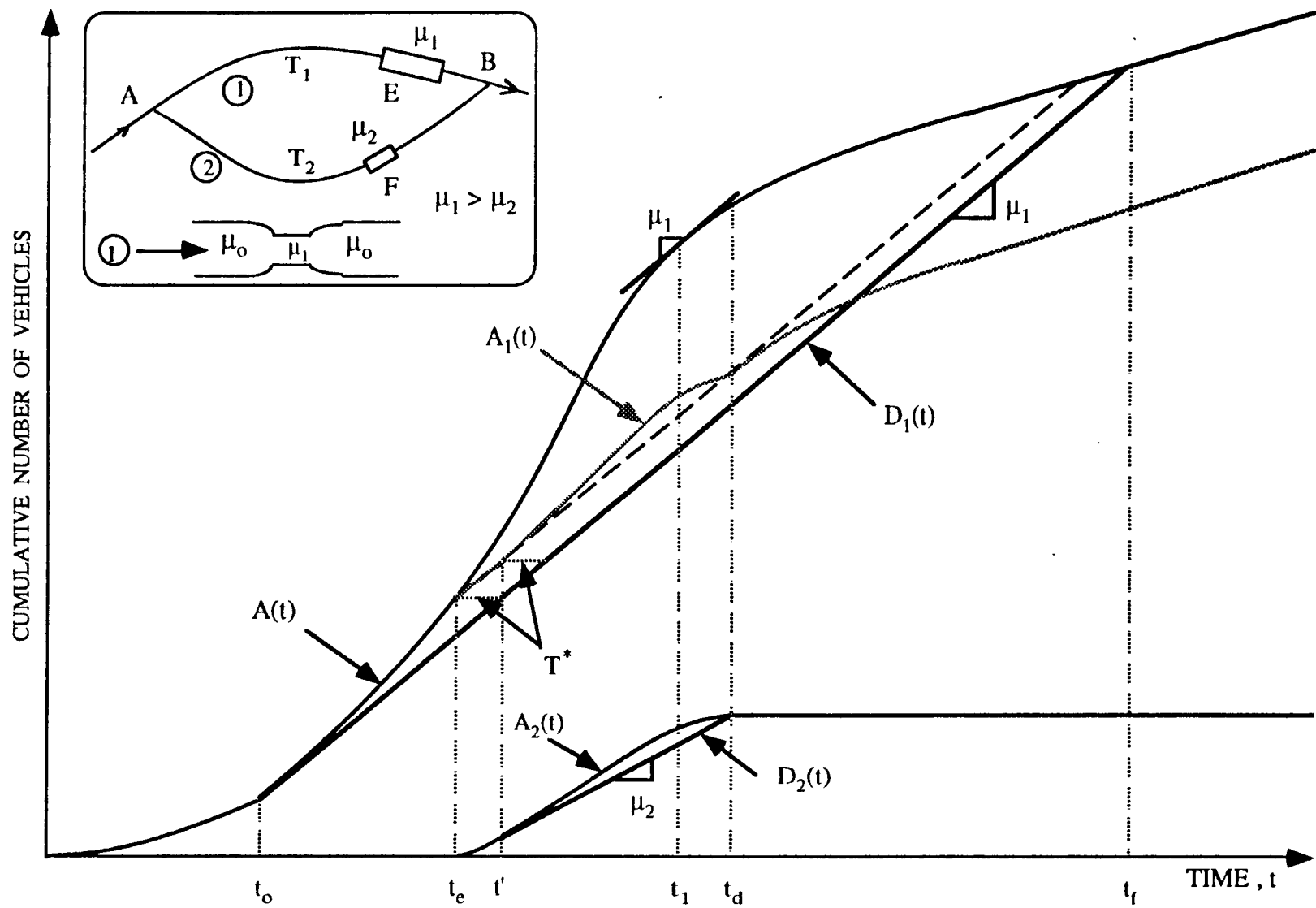


FIGURE 5.10 QUEUE EVOLUTION FOR THE PEAK PERIOD EQUILIBRIUM



$$A(t) = A(t) \quad \text{for } t < t_e$$

Equilibrium is maintained until time  $t_d$ . Given  $A(t)$ ,  $t_o$ , and  $T^*$ , it is straightforward to evaluate times  $t_e$ ,  $t'$ ,  $t_j$ ,  $t_d$ , and  $t_f$  from the queueing diagrams, where  $t_o$  and  $t'$  are the times when the queues start to form on Routes 1 and 2 respectively. This equilibrium will be established even if some travellers choose to use the longer travel time route. To maintain equilibrium, it is only necessary that a number of travellers sufficient to keep the route travel times equal behave in accordance with the assumptions of equilibrium assignment.

In Chapter 4 it was found that system benefits level off when both routes have busy bottlenecks. This finding is illustrated again in Figure 5.11.

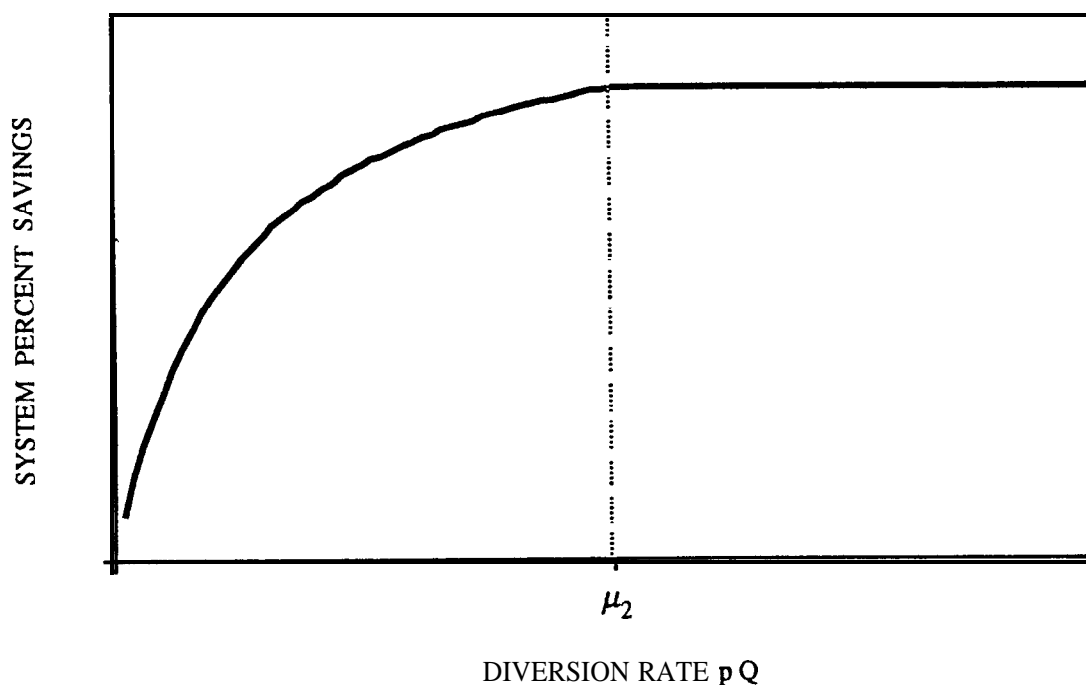


FIGURE 5.11 SYSTEM BENEFITS VERSUS DIVERSION RATE UNDER OFF-PEAK INCIDENT CONDITIONS

This figure shows that when the diversion rate exceeds  $\mu_2$ , the capacity of the alternate route, then no more system gains can be achieved with higher diversion rates. One can extrapolate this finding to the analysis of the, peak-period incidents. During the peak period

equilibrium the alternate route already has a queue as shown in Figure 5.10. If an incident occurs during the peak period equilibrium, then equilibrium will be interrupted. In order to return to equilibrium, **ATIS** vehicles will be diverted at rate  $pQ$  to the alternate route, thus joining the existing queue. It is expected that system benefits will not increase beyond that which can be achieved under the off-peak conditions, i.e when the diversion rate equals or exceeds the capacity of the alternate route as shown in Figure 5.11. Also system benefits during the peak conditions are reduced further because of the disbenefits caused to uavellers originally using the alternative routes where guided traffic is diverted. Hence, system benefits under the off-peak conditions represent an upper limit for the benefits of route guidance. This suggests that **ATIS** en-route guidance is more useful in the management of off-peak incidents. In today's urban networks, nearly half of the incidents occur during the off-peak period. For the incidents that occur during the peak period, the need is to spread traffic over time rather than space. This can be achieved through departure time switching rather than route switching. Here, the role of **ATIS** is thought to be more useful at home rather than en-route. This is yet to be investigated and is an interesting area for future research.

## 6. SUMMARY AND CONCLUSION

This study deals with incident management using **ATIS**. An off-peak incident is analyzed using deterministic queueing models in an idealized corridor composed of two routes. A user optimal strategy is implemented to disseminate real time **traffic** information to vehicles equipped with **ATIS**. The findings show that a few cases of queue evolution result when **ATIS** is used under incident conditions. Both the proportion of guided traffic and the incident duration play an important role in determining which case results. When the queue evolutions are determined, it is straightforward to find out whether **ATIS** is useful or not.

When an incident occurs, **ATIS** will divert all equipped vehicles to the alternate route until equilibrium is achieved. Once equilibrium is achieved, it is maintained by reducing the rate of diversion from one route to the other through pulsed diversion of **ATIS** vehicles. The implication is that during equilibrium some **ATIS** equipped travellers will be diverted to an alternate route while others will be asked to remain on the route where the incident has occurred. The benefits of **ATIS** measured as travel time savings are evaluated by comparing the queue evolutions with and without **ATIS**.

### **Synthesis of User Benefits**

The benefits to guided and unguided traffic are described as a function of the time of arrival at the junction upstream of the incident link. The results show that these benefits follow similar characteristics for all the cases studied. As long as the incident queue has not begun to discharge, the benefits to both guided and unguided traffic increase with the arrival time. When the incident queue begins to discharge, the benefits to guided traffic start to decrease while the benefits to unguided traffic continue to increase with the arrival time until equilibrium is achieved. As expected, the benefits to guided and unguided traffic are identical during the equilibrium period.

Guided traffic is better off than unguided **traffic only** during the diversion period that precedes equilibrium, but this advantage is drastically reduced when a queue does form on the alternate route or where equilibrium can be achieved. From the perspective of guided traffic, it is better to underestimate the incident duration rather than to overestimate it. **This** will guarantee that guided traffic will not be worse off with **ATIS** because of **over**-diversion. However, the cost of achieving this convenience to **ATIS** travellers is loss in system efficiency. From a system perspective it is better to minimize the magnitude of the prediction error in the incident duration regardless of whether this error is positive or negative. Clearly, there is a trade-off between convenience of **ATIS** travellers and system efficiency.

The benefits to guided traffic are insensitive to the fraction of vehicles equipped with **ATIS** as long as this fraction is below the critical value which causes a queue on the alternate route. The critical fraction is equal to the ratio of the capacity of the alternate route to the corridor demand. The critical fraction varies from zero to one. It equals zero when there is no alternate route, e.g the main facility is a tunnel or a bridge. It equals one in corridors with several major arterials, usually parallel to the main facility, that can absorb the corridor demand without being congested. When the alternate route is congested, the benefits to guided and unguided traffic become sensitive to the fraction of vehicles equipped with **ATIS**. The benefits to guided traffic decrease while the benefits to unguided traffic increase with this fraction. Thus, as the proportion of guided traffic increases, the gap in the benefits between guided and unguided traffic narrows consequently decreasing travellers' incentive to have **ATIS**.

### **Synthesis of System Benefits**

System benefits increase with the proportion of guided traffic as long as it is below the critical value that causes a queue on the alternate route, but do not increase with this proportion when a queue forms on the alternate route. As expected, system benefits also

do not increase with the increase in the proportion of guided traffic in cases where equilibrium can be achieved.

The results of sensitivity analysis indicate that system benefits increase nonlinearly with incident duration and severity. This increase has diminishing returns with respect to both parameters. As expected, the further the incident location is from the junction upstream of the incident link, the smaller are the benefits. The value of **ATIS** information declines as the capacity of the route with incident is improved. On the other hand, improving the capacity of the alternate route increases the system benefits of **ATIS**. It may be said that incident management using **ATIS** is an alternative to expensive capacity improvement projects for freeways but not to overall corridor capacity enhancement. Increase in the corridor demand means a larger incident queue on the freeway and therefore an increase in the potential savings from **ATIS**. If the alternate route is very long, it is as if it does not exist and **ATIS** becomes irrelevant. But when the difference in free flow travel time between the two routes decreases, diversion continues for a longer period of time and consequently diverted as well as undiverted traffic has a better chance to save time. Therefore, system benefits are expected to increase as this difference decreases and are maximized when the two routes have the same free flow travel time, e.g the two routes are parallel bridges connecting between two cities.

### **Estimation of ATIS Benefits**

Using the statistical results of two studies of real life incidents, the magnitudes of system and user benefits are estimated based on a best corridor scenario. This scenario is described as follows: the alternate route has ample capacity to absorb all the corridor demand without being congested, its free flow travel time is close to that of the main route, all traffic is guided with **ATIS**, all guided traffic follows instructions, and there is no loss of system efficiency due to information lag or error in the prediction of the incident duration...etc. Incidents are divided into truck related and non-truck related. For truck

related incidents, the upper limit of system benefits is 50%, while the upper limit of the benefits to **ATIS** equipped vehicles varies between 36% and 63% depending on the time of arrival to the junction upstream of the incident link. For non-truck incidents these figures are reduced nearly to the half (26% for system benefits and 17%36% for user benefits). The 'lower limit of the benefits is zero which is the case when no one can save time by being diverted to the alternate route. Under the best corridor conditions no benefit is achieved if the capacity reduced by the incident is less than 1% or if the incident duration is less than the time needed to reach the incident location.

Since truck-related incidents are rare (expected to be less than 5% of all incidents, Giuliano, 1989). the upper limits of the benefits for all incidents are biased toward non-truck incidents. About 80% of the non-truck incidents are vehicle disablements which generally do not cause lane blockages due to the availability of shoulders that can be used as emergency stopping areas. This explains why the benefits of **ATIS** for non-truck incidents are much less than the benefits for truck-involved incidents. In response to the growth in travel demand, however, the current practice in traffic management is to add freeway lanes by eliminating shoulders. If this trend continues, then the proportion of lane-blocking incidents is expected to increase in the future, which translates into greater potential benefits of **ATIS**.

## **Conclusion**

This research represents a modest **first** step toward understanding the role of **ATIS** in incident management. It provides a comprehensive analysis of the most relevant parameters that influence the benefits of **ATIS**, the most important among these is the fraction of vehicles equipped with **ATIS** (see equation 3-9). The critical value of this fraction that causes queues on the alternate routes does not depend on the incident parameters but it only depends on the corridor parameters: the capacities of the feasible alternate routes and the travel demand. Consequently it should not be difficult to estimate

this value in real life networks. The capacity that is used in calculating the critical fraction should be the total unused or available capacity of all the feasible alternate routes. It is not sufficient for an alternate route to be operationally feasible but it also needs to be institutionally feasible. In testing a few real life networks for this purpose, one may find that there are not many routes which qualify.

The benefits to guided traffic decrease when the proportion of guided traffic exceeds the critical value and system benefits also level off once this value is exceeded. Therefore, if the system management has the choice, there is no need to equip more than the critical fraction of vehicles with **ATIS**. Hence, the benefits to the system and to the **ATIS** equipped travellers will be maximized simultaneously. One expects that system benefits will saturate as the market penetration of **ATIS** reaches a certain level. This saturation reflects operational limitations of the highway facilities such as bottlenecks and the limited number of feasible alternate routes, as well as the lack of incentives by unequipped travellers to have route guidance.

In conclusion, route guidance has a significant role in the management of off-peak incidents. The main reason for this is the availability of uncongested alternate routes during the off-peak period. During the peak period, the alternate routes are usually congested. If an incident occurs during the peak period and **ATIS** vehicles are diverted, they join the existing queues on the alternate routes. Therefore, it is expected that system benefits for the peak period incidents will not increase beyond that which can be achieved under the off-peak conditions. Also system benefits during the peak conditions are reduced further because of the disadvantage caused to travellers originally using the alternative routes where guided traffic is diverted. Hence, system benefits under the off-peak conditions represent an upper limit for the benefits of route guidance. This suggests that **ATIS** en-route guidance is more useful in the management of off-peak incidents. In today's urban networks, nearly half of the incidents occur during the off-peak period. For the incidents that occur during the peak period, the need is to spread traffic over time rather than space.

This can be achieved through departure time switching rather than route switching. Here, the role of **ATIS** is thought to be more useful at home or before starting a trip rather than en-route. Pre-trip traffic information provides the most flexible decisions to trip makers. Travellers can switch routes, departure times, and possibly modes. This area is yet to be investigated and is an interesting subject for future research.



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