COMMUNICATION, INFORMATION AND RESPONSIBILITY DISTRIBUTION STRATEGIES FOR EFFECTIVE REAL-TIME TRANSIT SERVICE MANAGEMENT

by

David P. Barker

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Signature of Author ______________________________
Department of Civil and Environmental Engineering
May 24, 2002

Certified by ______________________________
Professor Nigel H. M. Wilson
Thesis Supervisor

Certified by ______________________________
Senior Research Associate Carl Martland
Research Supervisor

Accepted by ______________________________
Oral Buyukozturk
Chairman, Departmental Committee on Graduate Students

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Resolving disruptions is a continual challenge to providing quality, cost-effective transit service. While a number of recovery techniques exist to recover from disruptions, detecting a disruption, choosing a response and implementing it in a timely manner is a difficult task. Different agencies use different combinations of field supervision, centralized control, and traditional and advanced communication technology. While these different service management strategies have different results, there is no consensus on what makes a good strategy, nor a systematic method for evaluating a proposed strategy and predicting its strengths and weaknesses. The purpose of this thesis is to create a framework for studying bus service management strategies and draw general lessons from an application of that framework.

This thesis categorizes 15 distinct disruptions in bus service, the most common responses to each, and the information and resources necessary both to reach a decision on the most appropriate response and to implement it. It introduces a spreadsheet model for starting with the number of disruptions an agency faces and its chain of command for dealing with them and calculating the number of conversations that take place and the demand those conversations put on communications channels. Values gathered from studying Chicago Transit Authority (CTA) supervisor radio recordings allow this model to show the unused capacity of communications channels, if any, so that the feasibility of a prospective strategy can be determined.

This method of studying strategy is applied to CTA. It is found that CTA bus operations suffer from two bottlenecks. The control center relays delay reports too slowly for them to be useful, and the communications channels allotted to supervisors are less than they would be required to air all messages related to service restoration. As a result, street supervisors have few service restoration options available to respond to delays, and they lack the information needed to choose an option effectively. The net result is that minor delays typically go unaddressed until they deteriorate into major ones, and major delays impose greater cost on passengers than they should. The impact of adding handheld computers with real-time location information is studied, and it is found that this would let supervisors use a wider range of restoration techniques, allow them to choose the best technique more accurately, let them address minor delays before they become more serious and free the supervisory radio channels for more effective management of breakdowns, accidents and disturbances.

It is concluded that there are inherent advantages in managing schedule adherence from the field and managing incidents from a control center, regardless of an agency's level of communication investment. It is further concluded that digital messaging has a natural strength in dealing with routine and well-understood instructions, while voice communication is essential for tasks that are less predictable or require collaboration. Digital messaging can play a substantial role in a good service management strategy but can never replace voice radio.

Thesis Supervisor: Nigel H. M. Wilson
Title: Professor of Civil and Environmental Engineering

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Chapter 1: Introduction

Disruptions are unplanned problems that, if not addressed, will cause transit service to gradually or suddenly worsen. Some study has been put into the effects of certain disruptions and ways to abate or recover from them. These studies sometimes assume perfect information and sometimes assume very limited information. Other studies have looked at ways to distribute information or move decision-making, with the assumption that certain changes will improve the choice of recovery strategies. Few studies have looked at the difference that information can make, at the different ways it can be distributed, or at the capacity of a certain number of individuals to recommend and implement service management strategies based on the information they've been given. This thesis will study the effectiveness of different organizational structures and communication systems at allowing decision makers to resolve disruptions, and present an original methodology for studying the load on communication channels and individuals, thus allowing transit agencies to better plan communication investments and reorganization.

1.1 Disruptions and Recovery: The Context of This Research

Disruptions are unplanned events posing an obstacle to routine operation. Despite the implication of this definition, disruptions are routine in transit. A trolley breaks down, unable to carry its passengers and blocking the vehicles behind it. A passenger holds a subway door open twenty seconds for a friend, creating a slight imbalance in rush-hour headways. Construction blocks a street, stranding buses until they know how to reroute and adding travel time to the route. Other common examples of disruptions are:

accidents, wheelchair lift use, fare disputes, missed reliefs, late pull-outs, demand spikes, and traffic jams.

Left unaddressed, disruptions such as these can have a number of negative consequences. In the event of the use of a wheelchair lift on a busy bus route, the extra two minutes can be enough to put the bus behind schedule and lead to bus bunching. Passengers on board that bus and passengers waiting downstream are delayed. The driver may then arrive too late to pull out of the terminal on time for his next trip, prolonging the delay to the other direction; miss a relief, creating a delay on another route; or finish his run late, costing the agency overtime.

It is usually desirable or necessary for a transit agency to respond to a disruption in some way. Often there are several aspects to respond to. In the case of a late bus, changes may need to be made to the schedule of the line to minimize passenger wait time and agency overtime. In the case of a breakdown, the above also applies, but the agency must also respond with a repair crew that can either fix the bus where it stands or tow it to a garage. In the case of an accident, both of the above also apply, but the agency must also dispatch a supervisor and the police to each take their reports. In addition, relief problems generated by any of these incidents may need to be addressed, and vehicles on other routes might need to be held to allow for connections to be made.

A number of different service management techniques aimed at restoring regular service and recovering from a disruption have been used and studied. A delayed bus might be short-turned before it reaches its terminal; it might be expressed to a later point; its leader might be held, to pick up passengers that would otherwise be waiting for the delayed bus;

etc. Or there might be no service management intervention other than to let the bus finish its trip, hoping its recovery time at the terminal will be sufficient to let it start the next trip on time. Many papers have studied the costs and benefits of different techniques, usually approaching the problem from the point of view of a single omniscient and omnipotent decision-maker, knowing all quantifiable data and able to give any instruction to any vehicle. This is an excellent way to study different control strategies, but it differs significantly from the usual reality of real-time control.

1.2 Motivation

A wide variety of communication systems and strategies are in use throughout the world. At the Chicago Transit Authority (CTA), buses communicate digitally with a control center, which communicates verbally with supervisors in the field. At the Massachusetts Bay Transportation Authority (MBTA), buses, chief inspectors, radio cars and dispatchers all share one radio channel for their service area. These communication systems offer very different capabilities to decision-making personnel. At the CTA, the control center can track the location of individual buses and send text messages to an individual bus operators or operators en masse, but street supervisors cannot communicate with bus operators without going through the control center or visiting the bus in person. At the MBTA, buses cannot be tracked and there is no digital messaging, but supervisors and bus operators can communicate directly.

Different service management techniques require different kinds of information and communication channels. The CTA can easily hold buses ahead of schedule at certain points where street supervisors are stationed, but it is difficult to hold the leader of a late bus. The MBTA, having fewer street supervisors at points along routes, would find it takes more work to hold a bus that's ahead of schedule than at CTA, but thanks to easier communication it would be no harder to hold a late bus' leader. Even within the use of one service management technique, different communication systems allow for different variations of that technique. In a recent study Xuhui Yang found that vehicle holding supported with real-time information could be more precise than without, leading to a 38% reduction in passenger wait time (Xuhui Yang, 2002.)

Different communication systems enable an agency to use different service management techniques. Agencies across the country are beginning to make serious investments in technologies such as GPS, digital radio, digital messaging, cell phones, etc. As they look at technologies and choose among them, the fundamental question an agency must face is "how will this communications system allow us to improve service, and does it justify the cost?" Currently, there is no documented systematic method for answering this question in transit.

1.3 Purpose of This Thesis

This thesis studies the effectiveness of different organizational structures and communication systems in supporting transit personnel's efforts to recover from disruptions. The impacts of centralization and decentralization are considered. Communication technologies, including conventional radio, trunked radio and digital messaging are considered. This study is to produce information on which structures, and which technologies, effectively enable an agency to use particular service management techniques, and therefore how effectively the organization can then improve service.

This thesis also introduces a new methodology for assessing a transit agency's real-time decision-making capacity. This methodology takes the personnel deployment, communications system, service volume and disruption frequency data as inputs and produces the service management techniques that are available to recover from these disruptions as outputs. This methodology can also illustrate bottlenecks and potential areas of improvement. It is to be usable for diagnosing an existing system, studying a proposed organizational change, studying a proposed communications change, and studying change to both at once.

1.4 Method

The methodology has two parts. The first must be performed once to calibrate the model; the second must be performed for each use of the model.

In the first part, the author will categorize the different disruptions to which an agency can respond, the different service management techniques it can use, and how they correspond. He will break down each step of each service management technique, and determine what information is needed to effectively carry out each step, as well as what instructions must be given out. The author will categorize different communications technologies, and the amount of "strain" that relaying the above instructions and pieces of information takes.

The second part is to study an agency for a given time of day. Using knowledge of an agency's management structure, the author will map out who performs what step, who gives instructions to whom and what communication options people in different positions have available. From this, the model will derive what information needs to be communicated from the information people already have and the information each task requires. It will also derive what methods of communication can be used for these messages, based on the access people have and the abilities of different communication methods. Combining this information with the number of disruptions (and hence tasks) an agency faces and the "strain" each message takes will show the use of each communication channel, and the elimination of infeasible options will show the limits of the responses available to the agency.

1.5 Structure of This Document

Chapter two will serve as a literature review. This will include papers on the appropriateness of responses to disruptions, some existing service management strategies, some of their positives and negatives, and the study of organizations and communications.

Chapter three will provide a brief overview of different communication technologies currently available. The strengths, limitations and capacity issues of voice communication, digital messaging and direct contact, among others, will be described.

Chapter four will catalogue the different disruptions that can affect operation, the different service management techniques that an agency can employ, and how they correspond. The decisions that must be made to choose the most appropriate response and the information required for every step will be identified. Each disruption and service management technique will be described individually, and while broad generalizations will be made regarding the general usefulness or effectiveness of each technique, the thesis will not attempt to simulate the choice of an appropriate technique for a given situation, or attempt to demonstrate that any technique is categorically more useful than another. The importance of timeliness in information will also be described.

Chapter five will describe the model for appraising an agency's service management strategy. It will outline the assumptions, the theory, and the step-by-step instructions involved.

Chapter six will analyze the Chicago Transit Authority's bus operations, and serve as a walkthrough of the methodology used. The agency's actors and communication system will be described; the agency's volume of disruptions and assignment of responsibility will be described; the methodology will be walked through, step by step. The model will also be applied to study the introduction of a new communication system. The strengths and weaknesses the model indicates for each strategy will be described, and a recommendation of whether the change would be a significant improvement will be made.

Chapter seven will review the thesis and the analysis method, including its strengths and weaknesses. Conclusions will be drawn on effective service management strategies. Finally, future work will be suggested.

Chapter 2: Literature review

In this chapter, we will first review bus service management and the context of a bus service management strategy. We will look at the differences between some service management strategies, and some of the differences in their effectiveness. We will introduce an existing framework that could be applied to service management strategies, and observe where it is applicable and where it is lacking, notably in the role of communication. We will introduce a model used to study communications issues, and finally we will propose a means of combining these two models into one method, and outline the steps necessary to do so.

2.1 Context: Theory and Practice of Bus Service Management

An extensive body of literature exists describing the problems ("disruptions") that can occur in bus service and the effectiveness of various responses. One excellent guide covering numerous disruptions and responses is *Theory and Practice of Bus Service Management*, based on the restoration techniques used by RATP in Paris (Edith Froloff et al., 1994). This book details the problems that commonly occur in bus transit, the responses commonly applied, and what one must consider in choosing the most appropriate response. It begins by defining service management:

> "The OS [Operating Schedule] is the result of an optimization of the supply of service as a function of the objectives and the constraints of the operation. However, since this optimization is carried out in "anticipated time," it requires, in particular, the formulation of hypotheses on the conditions of traffic and the demand for service. Now, these two factors are complex phenomena, and are of an uncertain nature. This is why the OS can only define the modes of optimal functioning of the route for the average conditions of operation. As soon as one moves away from these

average conditions, it becomes necessary to manage the service in order to confront the degradation of the quality of service which arises from this drift.

"Service management is, therefore, the process of the adjustment in real time of the OS to operating conditions." (p 11)

There are many disruptions that can occur on a route. A bus can be behind or ahead of schedule. Buses can bunch together. A breakdown can occur, needing a repair or a tow and leaving the route with one less buss but just as many drivers. Supervisors face competing and conflicting goals, as well, principally headway regularity, schedule adherence, serving all passengers, getting relief drivers to relief points on time, and staying within budget. *Management* identifies fifteen different common restoration actions that address some of these goals:

"a) Six restoration actions at the originating terminal:

- jumping
- reassigning
- shift schedule time frame
- elimination of a departure
- insertion of a departure
- re-spacing of intervals

"b) Six restoration actions on the route:

- modification of the scheduled running times
- waiting at a bus stop
- bus change
- passing on the route
- exchange of drivers on the route
- deviation

"c) Three service management restoration actions which can be directed as required by the situation, at the terminal or on the route:

- the change of trip type by short-turning
- the change of the trip type by means of extension
- the change of the trip type by means of trip modification" (p 18)

(See chapter 4 for explanation of these response techniques.)

Management describes a number of situations for which the impacts of different responses are discussed. A wealth of information is provided for the reader to consider: the schedule of a route, branches, length, demand along various segments, relief points, traffic conditions, the nature and cause of a problem, and a time/space diagram showing every bus on the route are shown and their impact on decisions discussed. Of a route with even loads throughout it notes that when dealing with a late bus

> "the restoration action of a deadhead, which is intended to move a vehicle, as quickly as possible, to a point of loading is, therefore, not effective. In regard to short-turns, these are very poorly received by the passenger in this configuration. In case of a significant delay, the controller can be led to order dropping a round trip for one or several vehicles." (p 69)

On a route where the relief point is far from the garage, it observes that if a relief driver is absent then "a long time is necessary for a substitute driver from the depot to get to the relief point. The controller is often led to cancel the departure, with re-spacing, and to have the vehicle parked." (p 87)

These diverse problems offer the reader an opportunity to learn what makes one response appropriate for a given situation and another not. They also serve to illustrate one of the chief difficulties in service management. While it is already challenging to solve these problems when shown all information, a supervisor charged with making such a decision often knows a fraction of the information given in the book and is unable to use some of the techniques shown. For instance, if one bus is falling behind schedule, one technique is to hold its leader. But to do that a supervisor standing on the street must know the bus is late as its leader passes him or must be able to communicate with the leader when the late bus reaches him. The comparison is not strictly fair, but illustrative: a street supervisor and a service planner are both charged with creating an operating schedule, but a supervisor must do so with less data, with fewer tools, and in a fraction of the time. Because if he takes too much time, not only has the situation deteriorated (a route "tends to move away from optimum") (p 12, Edith Froloff et al., 1994) but other disruptions he is responsible for will begin to pile up.

This begs the question: what can we do to facilitate effective decision-making for service restoration? What information and tools should we provide, what tasks should we automate, how many people should oversee one route, how many routes should one person oversee, should a given disruption be managed by different people, how should they divide up the work, and who should have final authority?

An organizational structure with associated communications and computations systems provides a set of answers to these questions and is what is meant by *service management strategy.*

2.2 Some Basic Approaches to Service Management

The basic resources for service restoration are

- Point supervisors
- Mobile supervisors
- Dispatchers
- Communication
- Computer aid

There are many ways in which these resources can be combined. Some of the broad characteristics that differentiate service management strategies are

- Centralization – work and responsibility can be focused in the control center, or in the field
- Automation – tasks can be accomplished with much or little computer help
- Regionalization – people can be organized into groups overseeing different service areas or can be organized as one large unit
- Specialization – individuals can manage one aspect of many disruptions or all aspects of fewer disruptions

These characteristics are all relevant to the service management strategies described briefly below. In *Denver's Computer Aided Dispatch Automatic Vehicle Location System: The Human Factor Consequences,* Mary D. Stearns, describes the strategy of Denver's Regional Transportation District (RTD.) RTD operates a system of about 800 buses and two light rail lines, with 12 mobile supervisors and six dispatchers on duty at peak (there are no point supervisors.) A digital messaging system allows location tracking and digital messaging between all parties, and automation facilitates seeing all buses on a route. Voice communication is possible between dispatchers and supervisors with no delay and possible from buses to dispatchers or supervisors with some delay. The strategy is highly centralized and automated. Bus operators report problems to the control center, and schedule deviations are detected electronically and reported to the control center. If a situation can be addressed through instructions to bus operators a dispatcher will address it, otherwise he will dispatch a supervisor to the scene. This system has helped the agency be very effective at incident management and schedule adherence – on time performance increased from 88% to 90% between 1992 and 1996 despite increasing ridership (Mary D. Stearns, 1999.)

The Massachusetts Bay Transportation Authority (MBTA) operates a similarly sized bus system with about 800 buses, and also operates four subway lines and an extensive commuter rail network. (A bus rapid transit line is under construction at this writing.) They have 18 point supervisors, 18 mobile supervisors and two dispatchers on duty at peak. Each of two radio frequencies is applied to buses, supervisors and a dispatcher by service area, and supervisors have access to one additional frequency. Their system is regionalized, very decentralized and uses almost no automation. Buses that experience a significant disruption announce it over their radio channel and the supervisor assigns it to a supervisor, who handles all aspects of the disruption. Schedule and headway issues are dealt with almost exclusively by supervisors at terminals. This system helps the agency be effective at incident management but poor at schedule adherence – in a recent performance review, not one route achieved the agency's on-time performance goals.

The Chicago Transit Authority (CTA) operates a bus system of 1,800 buses as well as six rapid transit lines, and works in cooperation with Metra, which provides an extensive commuter rail network, and Pace, which provides suburban bus service. At peak it has over 60 point supervisors, five mobile supervisors and six dispatchers. Eight radio frequencies are available to bus operations. Most of CTA's buses have digital messaging, GPS and automatic voice channel management. Supervisors have ordinary radios and the control center has both but supervisors cannot communicate with bus operators except in person. Their system is specialized and not very automated. Two radio channels are allocated to supervisors and the balance to bus communication. Buses report problems to dispatchers, dispatchers may take some action but for most issues inform the supervisors of the problem. The system helped the agency be adequately with at incident management but is poor in terms of schedule adherence.

It should be noted that CTA's digital messaging technology has only been in use since 1999, and was originally intended to be part of a more complex system. The current dispatching technology, Bus Emergency Communication System (BECS,) was to be part of an automated schedule monitoring and adjustment system called the Bus Service Management System (BSMS.) This system would allow for centralized oversight of schedule adherence and headway regularity in the control center, where controllers would monitor routes and intervene to maintain schedule adherence. BSMS was designed to automatically suggest recovery techniques and automate their execution, and was intended to perform customer service tasks like automating stop announcements and updating real-time arrival signage at bus stops. For a variety of reasons CTA no longer plans to implement BSMS as described, although some of the underlying software would support a proposed modification discussed in chapter 6. The general opinion at CTA, as revealed in interviews conducted in the summer of 2001, was that BECS had made operations more difficult and been marginally detrimental to service quality.

Of course an agency's effectiveness at managing incidents or delays is not solely a function of its service management strategy. But the importance of service management cannot be dismissed either. When Tri-Met introduced digital messaging and bus tracking in Portland, headway variation declined by 15% in the peak. In an experiment, Tri-Met then modified the division of responsibility among supervisors and dispatchers to facilitate more service restoration techniques along its "transit mall" trunk corridors, causing another 9.4% reduction in variance along those corridors (James G. Strathman, 2001.) In Canada the Toronto Transit Commission (TTC) introduced vehicle tracking and centralized schedule monitoring in 1976 and experienced moderate increases in on-time performance despite a 30% increase in vehicular traffic and a 13-21% increase in ridership (Edward K. Morlok, 1993.) But what characteristics of a service management strategy make it effective or ineffective? Why did Denver, Tri-Met and TTC experience service improvements with GPS and digital messaging while CTA employees felt the change made things worse? How can an agency predict what changes in effectiveness a change in strategy may bring? And how can it choose a strategy that will improve performance?

2.3 Techniques for Studying Service Management Strategies

In his 1990 thesis, Robert Fellows devised an effective method for studying alternate management strategies for maintaining even headways on the MBTA's Green Line. The Green line is a very old light rail line with four branches and 200,000 daily passenger trips, and has historically been operated in a decentralized manner. Point supervisors manage headways and schedule adherence with radio and personal contact, while a dispatcher served primarily to coordinate emergency response. The MBTA was considering upgrading the Green Line's communication system to provide location information in the control center, and using that information to heavily centralize operations. Fellows' thesis compared the performance of the existing strategy with the likely performance of centralized operations.

Fellows drew on existing Green Line analysis to study the effectiveness of point supervisors' headway restoration decisions. He cited Deckoff's 1990 work, in which a spreadsheet model of observed restoration decisions showed that 73.8% of short turns reduced total passenger delay. Deckoff also concluded that by using different decision-making rules, supervisors could increase their success rate to 93.6% without any additional tools (and passenger time saved would increase from 9,400 minutes to 13,000 despite a reduction in the number of interventions.) He then studied the control center's likely abilities based on the information that dispatchers would have. He found that while the dispatcher would have more access to information about the line as a whole than supervisors do, they would not have access to the level of detail that supervisors have, and in particular "The resolution of the information provided by the [proposed] system may not be fine enough to provide an intuitive graphical representation of train spacing…" (p 85) and that the system would "fall short of providing much of the information needed to make the routine headway management decisions" (p 88) currently performed by supervisors. He concluded that, contrary to centralizing decision-making, "continuing the present division of authority, such that dispatchers continue to manage incidents and inspectors continue to control headways, may be the only way to capture the benefits of improved information and strategic control promised by the introduction of AVI." (p 146) His advice was heeded and the MBTA did not centralize its Green Line operations.

Fellows' thesis suggests the fundamentals of studying service management strategies. He studied what people would know under different circumstances, and how that would impact the quality of their service restoration decisions. The methods of Fellows' thesis, however, cannot be directly applied to bus service management. Most bus networks are significantly more complicated in total than one light rail line. The mechanics of headway and schedule restoration are different due to smaller passenger loads, larger headways, and mixed traffic. Bus operations' higher frequency of accidents, mechanical defects and route diversions make studying the effectiveness of incident management strategies as important as studying headway maintenance. Finally, there may be numerous routes that interact and far more vehicles, but far fewer supervisors per vehicle and fewer shared communications resources per vehicle. (The MBTA has 3.7 two-car Green Line trains per supervisor and 28 buses per supervisor. A national survey in 1991 found that 21 buses per supervisor was typical (Herbert S. Levinson, 1991.)) This makes effective division of labor and communication of information both more important and more difficult.

In Craig Phillip's 1980 thesis *Improving Freight Car Distribution Organization Support Systems: A Planned* Change *Approach,* he suggested a framework for studying a problem that reflects some of the complication of bus management: efficient distribution of empty cars on a large freight rail network. Phillip defines the goals of the process as "control tasks," and suggested the following approach to studying their effectiveness:

> "Based on previous research concerned with decision-making and organization behavior, three key dimensions of this [task] environment have been identified: (1) the organizational structure; (2) the information systems; and (3) the decision processes. Unfortunately most previous research has focussed (sic) on a single one of these elements; linking the analysis of all three together in a consistent fashion remains a significant challenge. Yet it is the linkage which is essential, since the problem here is to understand how changes in one dimension impact, and are impacted by, the other two dimensions.... by organizing the analyses of the three dimensions around these control tasks it is possible to understand how changes in one will impact or be impacted by the other two." (pp 21-23)

The fundamental building blocks of the distribution problem are a number of moving vehicles traveling over a large network, a network that must be managed in a way that continually brings the system closer to its ideal (no empty cars,) despite continuously changing circumstances and the impossibility of one individual knowing or understanding every system variable. Freight cars are not buses, but the problem is analogous to bus service management in slow motion. By defining the different control tasks of freight rail in the context of decision processes, organizational structure and information systems – and how those aspects interrelate – one can determine the effectiveness of a task environment at managing freight. By defining the different disruptions that must be addressed in bus service in the context of the steps of each decision and response, who has what responsibility, and how they communicate information – and how those aspects interrelate – one can determine the effectiveness of a bus service management strategy.

The steps of decisions and responses can be derived from the detailed analysis of responding to disruptions in *Theory and Practice of Bus Service Management.* Potential assignments of responsibilities to individuals can come from reviewing agency structure in the manner shown in section 2.2. What remains is a framework for studying communication.

2.4 Communication's Limits: The Burlington-Northern Study

In 1990, the Burlington Northern radio was considering a shift from voice dispatching to digital messaging, and needed to determine what impact such a change was likely to have. In *A Comparison of Voice and Data Link Communication: Railroad Dispatcher's Perspective*, John Vanderhorst studied the existing use of communication to answer questions such as "What does the dispatcher experience in using these media to communicate? What amount of communication is required of the dispatcher using these media? How long do communication exchanges take? What types of messages are communicated?" (p 6) He accomplished this by transcribing entire days of radio communication and noting the purpose of the communication, the information being conveyed, and the length of time the communication took. He then compared it to the way each task would be handled and how each piece of information would be sent using a proposed digital system. This allowed him to compare the difficulty of the task for the dispatcher and the speed of information delivery between the two systems, and served to demonstrate whether any messages were currently in use but would not be supported digitally. The analysis concluded that the change would reduce dispatcher workload, by making information easier to get and automating some processes, and would improve communications speed and efficiency by eliminating problems of weak radio transmission and multiple parties trying to use the radio at once.

This analysis was performed on freight rail, but the technique is applicable to bus communications. By studying the messages on a communication channel, the information given, the people giving it, the time spent, and the conflicts from overuse, one can gauge what needs that channel is meeting and what needs it is not.

2.5 Summary

Bus service can experience frequent, varied and unpredictable disruptions. A number of responses can be used to mitigate these disruptions, and determining the most appropriate response to a disruption, even on paper, is a complicated process with many variables. In transit service, those choosing a response do not have access to all the variables or all responses, and can make better decisions with more information and tools. Defining an organizational structure and communication system distributes information, communication and responsibility to give a decision maker the most information possible related to the decisions he makes.

Not all service management strategies are equally effective. Existing studies of similar topics suggest a method for studying a bus service management strategy. The steps necessary to respond to a disruption and the information required to do them well can be derived from existing literature studying responses to disruptions. The assignment of tasks to decision-makers can be derived from an organizational structure. The effectiveness of communication channels can be derived from studying the information that it needs to carry and its ability to carry it. Combining these approaches will show how quickly an organization can respond to a disruption, what techniques it can apply and how effectively it can choose between them. The more responses an agency has available to a kind of disruption and the more information it can use in choosing among them, the better the response chosen for each distinct disruption can be. This thesis will not determine the relative effectiveness of every response at dealing with every manner of disruption, but instead will understand that a strategy that enables more responses is more effective, and that certain types of responses are complimentary. This approach will lead to a demonstration of how well an organization can respond to particular disruptions using a given strategy, and an effective analysis of bus service management strategies.

Chapter 3: An Overview of Communications Channel Types

In this chapter, we will examine some of the communications options available to an agency. For each channel we will comment on who can use it to communicate, and with how many people at once; how quickly it can be used; what can be communicated; what the capacity is, and how service degrades as it approaches capacity; how reliable they are, in general and under specific circumstances; and how they can be recorded. The communications systems covered will include "open mic" radio channels, trunked radio, digital data, direct contact, cell phones, conventional and pay phones, and silent alarms.

3.1 Open Mic Radio Channels

Open mic radio channels are the most conventional form of radio, dating back to the start of the twentieth century. Fixed or portable radios can transmit sounds on a given radio frequency, and any other radio tuned to that frequency play the sound. Someone using the radio cannot speak over the frequency and listen to it at the same time. For wide areas, an agency may have "repeaters," large antennas that pick up signals and rebroadcast them in other areas, allowing for better reception over large areas. An agency typically has access to a fixed number of frequencies which it can use as it sees fit. Communications can be scrambled to prevent those outside the agency from eavesdropping, but typically are not, in which case anyone with a commercially available police scanner can listen in. It is not uncommon for news agencies to have scanners listening to radio transmissions, including those of transit agencies.

Anyone with an agency radio can speak on one of these frequencies, and everyone else on the frequency will hear it. While in theory one can start speaking as soon as one wants to – the moment someone pushes his radio key, his radio is transmitting – in reality not only must he wait for the frequency to be clear of other conversations, but he must get the attention of the parties relevant to his message, and for a busy frequency he may have to get permission from a central authority to speak. This, in addition to the end of the conversation, results in an average of about ten seconds of overhead for each conversation (see appendix B.) Almost any information can be communicated on an open mic radio, but if the signal is not scrambled, it cannot be used for information that must stay within the agency for reasons of public relations, customer or employee privacy, or security. The greater the amount of information transmitted, the greater amount of capacity, or time, is used (see appendix B.) Radio frequencies are vulnerable in a number of ways. Something as simple as one employee sitting on his radio's "talk" button can make a frequency virtually useless. Although radios are a very old and well-understood technology that can be built reliably, parts of individual radios still break in the field. If a repeater tower loses power or is knocked down in a storm, it can be difficult for people in one area to be heard by those outside it and vice-versa, although if a system is built with some redundancy the problem would be minor. Interference can also be a problem in severe weather. A radio frequency can be interfered with by those with ill intent by sabotage of the repeaters or transmission of static over the frequency. Agencies can record channels for quality assurance and legal liability purposes.

3.2 Digitally Managed / Trunked Radio Channels

This category refers to any kind of communication that is voice communication over radio waves but is not open mic. A central computer or special digital protocol between radios dynamically assigns the ability to speak and listen to certain frequencies according to the needs requested by the users. This means that the frequencies can be used for specific one-to-one conversations or conversations with groups of people. Trunked radio is relatively new, and different standards have different characteristics. Some increase the conversations that can occur per frequency, some do not. Some carry data, some do not. Some are secure and safe for confidential information, some are not. Time to set up a conversation can vary greatly, from an average time of 105 seconds from a bus' request to talk to the start of conversation at CTA (assuming immediate controller response) to an average time of 0.5 seconds with TErrestrial Trunked RAdio (TETRA,) which is being adopted by a number of European public service agencies. The technology used and the number of frequencies available both have an impact on conversation setup speed.

Digitally managed radio frequencies can offer the considerable advantage that a user can address a message to an arbitrary group of people determined on the fly, rather than a fixed group of people as with an open mic channel. If an agency is too large to contain all of its communications on one channel, this avoids the inefficiency of having to send some messages on both channels to reach everyone, and having to hunt through several channels to find a specific person. Also, by assigning different open mic frequencies to different regions or aspects of service, the demand on some of those channels can exceed capacity, while others go underutilized. This can happen consistently, as it is rarely possible to divide the frequencies between functions such that each will have an equal amount of demand, and it can happen sporadically, as an unusually large number of disruptions occur at once in a given aspect of service. By assigning frequencies to conversations dynamically, trunked radio makes the only constraints to establishing communication the number of frequencies available and the availability of radio users.

If a radio system is managed by a central computer, as is common, a failure in the computer can lead to a failure in the communication system. Depending on design and the nature of the failure, the radios may become entirely inoperative, or could revert to a fixed-frequency system. A digital radio system is less vulnerable to jamming or interference, as interference with one frequency reduces the capacity shared by everyone using the digital system, rather than eliminating the capacity of everyone using the given frequency. In other ways, such as with the use of repeaters, trunked radio is like open mic radio.

3.3 Digital Messaging

The transmission of digital messages can occur either over wires or over a dedicated radio frequency. Transmission over wires is most often done with a "broadcast" protocol, such as Ethernet, which is decentralized. Due to the higher lag time of radio, communication over the air is more often through "polling," in which all messages go through a central computer. Digital messaging has several advantages not found in voice communication, and also its own drawbacks.

Digital messages can go from anyone with a digital message unit to anyone with a digital message unit, including a number of recipients simultaneously. A computer program performing simple service management tasks automatically could be the sender of the message, the recipient, or both. A message might also contain some information from a person and some from a computer, as when a bus driver sends a breakdown report and the on-board computer includes the bus' location in the message. The capacity of a digital messaging frequency allows for many more messages to be sent during an hour over one frequency than would be possible with voice. Messages can be automatically queued for the recipient, allowing them to finish the task they are working on before reading the message, and allowing multiple senders to send messages to the same recipient simultaneously.

The drawbacks of digital messaging include the cost, the limitations on what messages can be sent, the speed and accuracy of sending a message, and its inability to support a conversation. A digital messaging system can only send the messages that it was designed for. This limits the amount of detail that can be given about a situation. If a bus operator can only send a message saying he has a mechanical defect, voice communication is necessary for the respondent to determine the severity of the defect and the most appropriate response. The more messages are made available to send, the more complicated the system, and the greater the chance of operator error. More messages available for sending also mean that it takes longer to enter the message to be sent. If a bus operator wishes to report that he is behind schedule, it may only take him ten seconds to send the message using an open mic, and he may be able to do it when the bus is in motion. If it takes him one minute to enter the report into a computer, and he must pull over to do so safely, he is now an additional minute late. Dispatchers and mobile supervisors may have access to systems with keyboards, allowing them to send whatever text message they wish, but this is unwieldy for street supervisors and bus operators, who must usually choose a limited number of messages from a menu. The limitation on what data can be sent also limits the possibility of collaborative problem solving over the communications channel, which is more difficult without the freedom to explain whatever details are thought relevant and the nuances of voice communication.

Digital messaging handles excess demand more gracefully than open mic or trunked radio. Messages may be relayed more slowly, but it would take a prolonged and exceedingly high demand to delay messages more than several seconds. Communication over wires is dependant on the condition and security of the wires, while communication over the air is dependant on all the factors found in any radio system (see section 3.1) and the operation of one central computer. Digital communication is more susceptible to repeater tower failure than voice communication. If a repeater tower is disabled, people on voice radio can often be picked up through another tower, and need only to shout and repeat themselves to be heard over the static. Data units cannot always compensate in the same way. One cannot eavesdrop on data messages without equipment and inside knowledge, so they are appropriate for confidential communication. Not only can agencies record digital messages for quality assurance and legal liability purposes, but they can also use the stored information to study service issues – searching the data automatically to find out how many delay reports were sent during a particular time of day, for example. (For an example of this application, see section 6.1.2.)

3.4 Direct Contact

Direct contact refers to people in the same place communicating with each other without any kind of technology. It goes without saying that anything can be said, nothing is recorded, the only capacity issue is the limit of what one person can do in a given period of time, and personal contact is not susceptible to malfunction or sabotage.

The constraining aspect of direct contact is that it can only occur between people who are in the same place, while transit agencies are most concerned with moving objects. This means that messages between a bus and a point supervisor cannot be given by direct contact until the bus reaches the point supervisor, at which point the bus must hold in that place until the conversation is finished. Messages between a bus and a mobile supervisor can only occur if the mobile supervisor seeks out the bus, which depending on the situation may mean that some other method of communication was necessary to initiate the process.

This constraint and the awareness of bus locations and conditions in the supervisor's line of sight are the principle factors to consider when deciding where along a bus route a point supervisor can do the most good. Placement of street supervision is an involved topic, of too much depth to explore fully here. Broadly, supervisors at terminals are better equipped to reschedule the street and manage route-wide issues, while supervisors along the route are better equipped to manage headways and make schedule adjustments to individual buses. See chapter four for more information on these problems and recovery techniques.

3.5 Cellular Phones

Cellular phones allow their users to communicate with any other individual with a phone. It takes on the order of thirty seconds to establish communication with another individual, and longer to establish communication between three people. They are normally used for communication between two people, as communication between three is usually unwieldy.

Cellular phones make bandwidth an issue of the supplier, rather than the agency. This can be positive, when a major disruption causes an agency to need much more capacity than it would ordinarily budget for, or when an issue would benefit from a prolonged discussion between two people that would be impractical on an open mic system. It can also be negative because this capacity is shared with the provider's other customers. A company may routinely have insufficient capacity during certain times of day, and when significant regional events increase overall cellular demand it reduces the value of the phones to anyone. Cellular phones are also less reliable in certain areas and do not usually function in tunnels.

Notably, conversations between two cellular phones cannot be conveniently recorded for quality assurance or legal liability purposes. The only records available are when conversations took place, whom those conversations were with, and how long they lasted. Liability issues have caused some agencies (including the Massachusetts Bay Transportation Authority) to phase out all cell phone use. An adequate number of trunked radio channels is superior to cell phone use in almost every way. The advantages cellular phones provide over digital radio is that they may be cheaper and faster to deploy, and their bandwidth is not a constraint in the event of a major agency disruption that is not accompanied by a regional emergency. Eavesdropping on them is almost impossible and they are suitable for confidential communication.

3.6 Conventional Phones and Payphones

Conventional or "land line" telephones are far more reliable than cellular phones. Though sometimes phone lines are damaged during heavy storms, it is very rare for a phone switch to be overloaded by anything but a major regional emergency. Land line phones are less expensive than cellular phones, and conversations can be recorded, although this can be more expensive and problematic than recording voice radio if the calls do not all go to a small number of central facilities. In other words, if a supervisor at one bus terminal telephones a supervisor at another bus terminal, the conversation would not be recorded if neither terminal had recording equipment. With the above exceptions, the only difference between conventional and cellular phones is a cellular phone's mobility.

Supervisors or bus operators can use payphones if they are nearby. They can start a call but they cannot be called. Payphones are sometimes used for routine messages that are not time-sensitive, such as a reminder to the control center that a problem still has not been resolved, or for relaying information too sensitive for the radio, such as the details of an accident. While payphones are on the same network as conventional phones, the payphones themselves are often unreliable. Dependence on pay phones outside city centers may not be a viable long-term strategy. The increasing popularity of cellular phones is taking business from payphones, and as a result phone companies are disconnecting an increasing number of now unprofitable pay phones (Jon Auerbach, 1994.)

3.7 Silent Alarms

Silent alarms can work in several different ways and could be part of a number of the categories listed above, but are listed here because of their unique qualities. A silent alarm is a distress signal that a bus operator can send without the passengers' knowledge. As such it is designed for use only in emergencies and must be transmitted reliably. It is the only message for which the sender himself cannot add any more information, and in the event of a sensitive or broken switch, it is the only message that can be sent accidentally without the sender's awareness.

A silent alarm can be as simple as flashing lights on the front of a bus and a destination sign that reads "NEED HELP – CALL POLICE." Such a system relies on a passerby to take the initiative to find a phone and call 911. A more reliable system is a silent alarm that sends a radio distress signal. This signal could be audio, digital, or a combination of the two. It must indicate the bus or run number so that the recipient, usually the control center, can dispatch police or supervision to look for the appropriate bus. Other information may include the bus' location, whether the bus is moving, and a hidden microphone broadcast of events on the bus. Transmitting the image from a security camera is also possible, but the author does not know of an agency that does so. This information can help authorities find a bus faster and be better prepared to intervene. Because a silent alarm must be fail-safe, its signal is rarely scrambled, and it cannot be deactivated remotely.

It is clearly critical that a silent alarm work when activated, but it is also important that silent alarms do not often go off by mistake. False alarms create unnecessary work for supervision or police, and several simultaneous silent alarms with hidden microphones can take up most of an agency's communication channels, hindering their ability to respond to the alarms or to anything else. If two buses send silent alarms on the same frequency at the same time, one alarm false and the other an emergency, it may be very difficult to hear what is happening on the bus experiencing an emergency, or even to determine which transmission is which. Silent alarms are a powerful safety tool, but poorly installed or maintained they can be as much a liability as they are an asset.

3.8 Summary

The following highlights can be drawn from the preceding descriptions:

- A good trunked radio system, while more expensive than conventional radio or cellular phones, combines the benefits of both: reliability, capacity, flexibility, and the ability to be recorded.
- Digital data can be faster than voice communication and can give frequencies more capacity, but is not a substitute for voice communication. Some messages cannot be conveyed digitally and wireless digital systems are vulnerable to interference and centralized failure.
- Digital data, with its ease in reporting and compiling locations, can be particularly useful in managing headways and schedules; voice communication, with its flexibility and allowance of detail, is particularly useful for responding to breakdowns, accidents and disturbances.
- Pay phones are an appropriate means of communicating a slim minority of messages, but may become too sparse to be useful in the future.
- Silent alarms can be a valuable safety tool, but can be very disruptive to communications and operations if inadequate maintenance results in many false alarms.

Chapter 4: Situations and Responses

A transit agency of any size experiences a certain number of disruptions during the course of its workday. While each of these disruptions is unique – no two accidents are exactly alike – they can nonetheless be placed in broad categories that have much in common. For every mechanical breakdown that disables a bus, there is a common set of problems to be dealt with, a common set of decisions that must be made, and a common set of potential responses. Determining these categories, these decisions, and these responses is an important part in modeling any aspect of service restoration, and is the purpose of this chapter.

We will first describe the disruptions that arise during transit service, and the most common techniques used to deal with them and restore service. We will detail what real-time information and general knowledge is necessary to implement these service restoration techniques. We will outline the decisions that must be made to choose the best response, ultimately presenting charts of all steps that might be taken in dealing with a typical disruption. Finally we will examine the importance of timeliness in responding to these events.

4.1 Common service disruptions

In this section, we present a list of the fifteen most common forms of disruption and one situation that is not a disruption. This list is intended to include the disruptions that occur regularly in the provision of transit service. It is not intended to include every problem that conceivably could occur during transit service. One can imagine, for example, a dual-mode bus that suffers an electrical failure, preventing itself from following its scheduled route through an exclusive bus tunnel but not preventing it from serving a route for which it is not scheduled. Such a scenario would not fit cleanly into the situation list below, however it is not likely to be a common occurrence for most agencies. Agencies using the methods outlined in this thesis should stop to consider if their bus operations have any frequent problems that are not represented in this list.

The following disruptions will be covered:

4.1.1 Bus early
4.1.2 Bus delay (short headway route)
4.1.3 Bus delay (long headway route)
4.1.4 Crush load (one bus, not delayed)
4.1.5 Mechanical problem (minor - bus movable)
4.1.6 Mechanical problem (serious - bus movable without passengers)
4.1.7 Mechanical problem (major - bus immobilized)
4.1.8 Emergency / Security / Fare Dispute
4.1.9 Accident
4.1.10 Operator Misses Relief
4.1.11 Blockage
4.1.12 Bus Standing / Service Gap
4.1.13 Unfilled Run
4.1.14 Unplanned Bus Bridge
4.1.15 Congestion / Weather / Route-wide Crowding
4.1.16 Late Pull-Out

The selection and organization of items on this list is a synthesis of the material in *Theory and Practice in Service Management* (Edith Froloff et al., 1994), the original Bus Service Management Systems specification (Lawrence Wilson, 1992), and the Chicago Transit Authority's Bus Emergency Communications System program structure.

4.1.1 Bus Early

A bus is early if it is ahead of its schedule. An early bus may or may not be a problem. Imagine a route that runs every half hour, collecting passengers in the suburbs and then taking a highway to a downtown transit center. If the bus is ahead of schedule in the middle of the collection portion of its route, passengers who arrive on time will miss the bus, so that is a problem. If the bus makes unusually good time on the highway, that is not a problem, as no one else is expected to board. In this paper, "bus early" refers to any time a bus is early, whether it is actually a disruption or not.

4.1.2 Bus delay (short headway route)

A bus is delayed if it is behind schedule. Delays are the most common kind of disruption for many agencies, and there are many potential ways to divide them into categories. For our purposes, delays will be divided into routes with short or long headways.

A "short headway route" can be approximated as any route with a headway of ten minutes or less, but can more accurately be described as any route for which most passengers show up randomly, or any route on which a delayed bus is likely to lead to bus bunching.

4.1.3 Bus delay (long headway route)

For our purposes, a "long headway route" can be approximated as any route with a headway of greater than ten minutes, but can more accurately be described as any route for which most passengers time their arrival at the bus stop according to the bus' scheduled arrival.

4.1.4 Crush load (one bus, not delayed)

Delayed buses are often crowded, but it is also possible to have an excessively crowded bus that is still on schedule. The crowding increases the probability that the bus will fall behind schedule, but as it is sometimes possible to proactively address this problem before the bus becomes late, crush load is included here as its own condition.

4.1.5 Mechanical problem (minor - bus movable)

Mechanical problems can also be subdivided in a number of different ways; however for our purposes they will be divided into problems leaving the bus movable and in service, problems serious enough to prohibit passengers from riding the bus, and major problems which immobilize the bus entirely. Examples of minor problems include disabled climate control, leaking roof, or a broken wheelchair lift or farebox. Depending on agency policy, a broken lift or farebox may be considered a serious mechanical problem, but in general a minor mechanical problem is any problem that is unpleasant, but not so troublesome that it is worse than providing no service at all.

4.1.6 Mechanical problem (serious - bus movable without passengers)

A serious mechanical problem is any problem for which the bus can still move, but the agency cannot use the bus to carry passengers. The most common kind of serious mechanical problems are safety problems, such as broken doors or a smoky interior.

A serious mechanical problem gives rise to an unfilled run (4.1.13) and a service gap (4.1.12.)

4.1.7 Mechanical problem (major - bus immobilized)

A major mechanical problem is any problem for which the bus is immobilized. Examples of major mechanical problems include dead motors, worn-out clutches, and faulty brakes.

Major mechanical problems often result in an unfilled run (4.1.13) and a service gap (4.1.12.)

4.1.8 Emergency / Security / Fare Dispute

A disruption in this category could be something as simple as graffiti in process to something as grave as an assault on a driver, and could also include sick passengers. While these situations may ultimately require very different responses, they are deliberately combined into the same category because learning the severity of a problem is often difficult. A silent alarm on a bus could go off by mistake, or could indicate grave danger, and the agency must often take action without knowing the severity of the situation.

Emergencies often occur with a bus delay (4.1.2, 4.1.3.)

4.1.9 Accident

An accident is any situation in which the bus makes contact with another object outside the agency's garage. Like emergencies, accidents have a wide range of type and severity that govern the urgency and degree of response.

Accidents often give rise to a mechanical problem (4.1.5, 4.1.6, 4.1.7), an unfilled run (4.1.13) and a service gap (4.1.12.)

4.1.10 Operator Misses Relief

An operator missing a relief occurs when a bus driver arrives at a relief point expecting to be relieved, and his relief is not present. An operator not reporting to a garage to begin a run is not considered a missed relief for our purposes; if no driver can be found within the garage, it would be considered an unfilled run (4.1.13.)

The frequency of this disruption, and the appropriate service restoration techniques, vary tremendously from one agency to another. They are both greatly impacted by work rules and agency policy. This thesis will use a generalized framework of possible responses, which most agencies will need to adapt to their own situation.

4.1.11 Blockage

A blockage is any condition on a route that prevents buses from traveling along a portion of the route. A blockage can be the result of a flooded street or a fire, or it can be as simple as a broken railway gate or double-parked car. Blockages can usually be bypassed on different streets, but this reroute must be managed so that buses can do so consistently and without getting lost.

Blockages often result in bus delays (4.1.2, 4.1.3) and may prompt the equivalent of an unfilled run (4.1.13.)

4.1.12 Bus Standing / Service Gap

A service gap refers to the adjustments that must be made to provide the best service possible on a route operating with one fewer run than usual. This can be caused by a bus standing instead of being in service or by an unfilled run. Many of the situations in this list create a service gap.

4.1.13 Unfilled Run

An unfilled run is the absence of both a bus and a driver needed for a run. The difference between bus standing / service gap, above, and an unfilled run refers to the different aspects of the problem of not having a bus and driver ready for a scheduled trip. Bus standing / service gap refers to the need to manage service without the run. Unfilled run refers to the effort to restore the run. An unfilled run implies a service gap, but a service gap does not imply an unfilled run. A situation in which a driver is present without a working bus (such as a mechanical failure) or a bus is present without a driver (such as a missed relief) is not considered an unfilled run, as they are addressed in different ways.

4.1.14 Unplanned Bus Bridge

A bus bridge (or "shuttle") is not itself a disruption, but is a service necessitated by a rail disruption. A bus bridge is necessary when a portion of a rapid transit line is shut down, requiring bus substitution. It is only applicable to agencies that have a rail component, or share an operating area with an agency that has a rail component. Unplanned bus bridges require the agency to provide a great many buses and drivers at once, usually pulling some of them from other routes. While some aspects of a bus bridge can and should be planned ahead of time, such as what routes the buses should take, the route must be managed more actively than other routes because there is no set schedule for its drivers to follow. Therefore headway management, and especially putting the buses in place as the bridge begins operation, requires active oversight.

4.1.15 Congestion / Weather / Route-wide Crowding

Sometimes conditions occur which adversely affect most of a route, or a number of routes. When this occurs, the route's schedule can become impossible to adhere to, and the route can become over-crowded, with each condition contributing to the other. This category carries a wide range of severity, from a slowdown due to construction to heavy snowfall; a true system-wide emergency, though, like rampant flooding, is outside the scope of this thesis.

4.1.16 Late Pull-Out

A late pull-out is not a disruption, but still a service event that must be addressed. A late pull-out signifies the end of an unfilled run. The techniques that were started to deal with the unfilled run should be stopped when the late pull-out is put in place.

4.2 Recovery Techniques

In this section, we present a list of the 29 most common recovery techniques agencies use to restore service in the event of a disruption. This list is intended to include the techniques used fairly regularly by a number of agencies and is not intended to include every technique that an agency could conceivably use. The resourcefulness of managers in the field often leads to one-of-a-kind creative responses to unusual combinations of situations. Furthermore not all of these responses will be available to all agencies. One agency might have no mobile repair trucks, another might have strict work rules that prohibit drivers from driving runs other than those they are assigned.

It should also be noted that signal priority does not appear on this list. It is assumed that if an agency uses signal priority in its operations, it happens automatically based on the bus' location and perhaps schedule adherence. The interventions appearing on this list are only those for which some human intervention is required.

The techniques in this list are broken into five broad categories: managing headways and schedules, solving mechanical problems, managing reliefs, providing additional or altered service, and managing emergencies. They are listed by category in Table 4-1. These categories are intended to organize the list, rather than definitively state the purpose of the techniques in it. A number of techniques could have fitted equally well into several categories.

Table 4-1: Response Techniques by Category

#	**H** *Headways/schedules*	**M** *Mechanical problems*	**R** *Reliefs*	**A** *Additional service*	**E** *Emergencies*
1	Hold bus	Supervisor repairs bus at terminal	Wait for relief	Use standby bus	Bus continues to point supervision
2	Hold leader	Supervisor repairs bus on site	Relief operator relieves other than scheduled operator	Fill from another street	Dispatch mobile supervision
3	Drop off only	Truck repairs bus on site	Relief operator relieves scheduled operator later	Fill with pull-in	Dispatch police and/or medics
4	Express to a later point	Maintenance brings bus change	Pull in	Put bus in place	
5	Express down a different street	Maintenance tows bus	Pull out instead of relieve	Emergency reroute	
6	Short turn	Pulls in/out	Operator exchange		
7	Follower picks up passengers	Jump buses			
8	Spread the interval				
9	Spread the terminal / reschedule street				

The selection and organization of items on this list is a synthesis of the material in *Theory and Practice in Service Management* (Edith Froloff et al., 1994), the original Bus Service Management Systems specification (Lawrence Wilson, 1992), and observations made at the Chicago Transit Authority.

4.2.1 Managing Headways and Schedules (H)

H.1 Hold Bus

Holding a bus means having the bus driver wait in one place, usually at a stop, for a set amount of time before resuming progress along its route.

For our purposes, hold bus refers only to holding a bus to benefit that bus, to deliberately slow that bus down. For holding a bus for the sake of its follower, see "hold leader," below. To hold a bus, it is necessary to know how long to hold the bus for, which can be is a function of the bus' current location and the schedule.

H.2 Hold Leader

Holding a bus' leader means having a bus' leader stand in place for a specified number of minutes. By holding its leader, the bus' leading headway is reduced, resulting in less passengers waiting to board this bus. This can help a bus travel faster.

Because holding a bus' leader is a fairly common and powerful technique, it is worth discussing two common variations. In conventional or "normal" holding of a leader, the leader of a late bus is held until the late bus' leading headway is equal to the route's scheduled headway. This means that the held bus' leading headway is now about equal to the late bus' leading headway before holding. The gap in service has not been eliminated so much as it has been moved further up the line to a less crowded bus. This technique requires knowledge of the positions of the late bus and its leader.

With "prefol" holding of a leader, an abbreviation of "preceding – following," a bus' leader is held until that bus' leading and following headways are equal. Say buses A, B, and C are operating on a route with 8 minute headways, with A in the lead. Bus C is two minutes late, giving it a 10 minute leading headway. Under normal holding of a leader, bus B would be held 2 minutes to restore bus C's leading headway to normal, giving it a headway of ten minutes. Under prefol holding of a leader, bus B would be held one minute, giving buses B and C each 9 minute headways. Prefol holding "dissipates" a delay, so that it can do less damage. In 2001, Xuhui Lang found that prefol holding led to a 38% reduction in passenger wait time compared to conventional holding. This technique requires knowledge of the positions of a late bus, its leader, and its leader's leader.

H.3 Drop-off Only

Drop off only refers to allowing passengers to exit, but not allow boardings, for a portion of the route. This allows the bus to operate faster than it otherwise would, while inconveniencing passengers who are not allowed to board and must wait for the next bus. The increase in speed is not as great as that from expressing, but no passengers are forced to alight and wait for local service as with expressing, and no "follower picks up passengers" (H.7) is necessary. To operate drop-off only service, a bus operator must know the portion of the route for which he is to do so, which is a function of position, schedule, and the expected time savings.

H.4 Express to a Later Point

Expressing refers to proceeding along a portion of a route without stopping at scheduled stops to pick up or discharge passengers. This allows the bus to travel faster than it normally would, but it inconveniences passengers who would otherwise have exited or boarded during the express portion of the trip. Passengers who would have exited must exit beforehand, and then both sets of passengers must wait for the next bus. It is necessary for the follower to pick up passengers (H.7) so that no passengers are charged an extra fare. To express to a later point, an operator must know the portion of the route for which to express, which is a function of bus position, schedule, and the expected time savings.

H.5 Express Down a Different Street

Expressing down a different street is similar to expressing to a later point, except that the bus operator takes a different route than usual to get from the beginning to the end of its express portion. This is a useful variation if a street network happens to offer a faster alternative to a portion of a route, which could be as simple as a parallel arterial or as complicated as any set of directions. Having the follower pick up passengers (H.7) is still required. Unlike when expressing to a later point, the driver needs to know not just the starting and ending points (a function of bus position, schedule, expected time savings, and street geography) of the expressed portion, but the alternate routing in between.

H.6 Short Turn

A short turn occurs when a bus operator does not proceed to the end of his route as scheduled, but instead discharges his passengers, turns around, and starts a trip in the return direction from a point after the normal beginning of the trip. This can bring a very late bus back to schedule with one action, but is an inconvenience to discharged passengers and passengers in either direction who cannot board this bus. To execute a short turn an operator must know at what point to turn, which is a function of the bus' position and schedule. It is also necessary for the follower to pick up passengers (H.7.)

H.7 Follower Picks up Passengers

In this instance, the follower of a bus that was disabled, expressed, etc. allows passengers to board for no fare. This may require the follower to know to allow passengers to board freely, or it may require the affected bus driver to distribute transfer tickets to discharged passengers, depending on the fare system the agency uses.

H.8 Spread the Interval

Spreading an interval refers to closing a gap on a route that has had a bus taken out of service while on the street. If the agency has control over signal priority, this may involve holding the gaps' leader and increasing the speed of the gap's follower until the gap's length, the gap's leader's lead headway, and the gap's follower's following headway are all equal. Spreading the interval can also involve only the gap's followers, the gap's two leaders and two followers, etc. as dictated by the severity of the situation and the abilities of the agency. Spreading the interval therefore requires the immediate, coordinated action of several buses based on their location.

H.9 Spread the Terminal / Reschedule Street

Spreading the terminal refers to changing the headway of a route to reflect a loss or gain of a bus operating on the route. For instance, if a route with a one hour cycle time and five minute headways normally operates with 12 buses but loses two of them, the terminal could be spread to six minute headways to minimize passenger impact. Spreading the terminal requires the coordinated action of each bus departing a terminal.

4.2.2 Solving Mechanical Problems (M)

M.1 Supervisor Repairs Bus at Terminal

This action is self-explanatory. If a supervisor is stationed at the terminal, then no advanced notice is even necessary. He can attempt to repair the bus when it arrives (or does not start.) If no supervisor is stationed there, the action would be more accurately considered a repair of the bus on-site (below.)

M.2 Supervisor Repairs Bus on Site

This action refers to a supervisor repairing a bus at the place where it becomes disabled. This generally means having a mobile supervisor travel to meet the disabled bus, requiring that the supervisor know the bus' location.

M.3 Truck Repairs Bus on Site

This refers to a mobile repair truck driving to the site of a disabled bus and attempting to repair it. As with a mobile supervisor, the repair truck must know the bus' location.

M.4 Maintenance Brings Bus Change

In this case a "runner" drives a bus from the garage to meet the driver of a bus that has experienced a mechanical defect, in order to allow that bus driver to resume his run with the new bus. The runner returns to the garage with the disabled bus, driving it in himself if it is not immobilized, or riding with the tow truck if it is towed back (below.)

M.5 Maintenance Tows Bus

If a bus cannot be repaired on-site, the only remaining option is to tow it to the garage.

M.6 Pull In/Out

When a bus is experiencing problems but is still movable, one option is for the bus operator to drive the bus to the garage and drive out with a different bus. This is a combined pull in and pull out, or "pull in and out."

M.7 Jump Buses

This recovery technique allows all trips on a route to be served if there are enough drivers but one fewer bus than necessary. If the recovery time at the terminal is greater than the route's headway, under normal operation there will always be at least one driver on break at the terminal and one bus standing there, and they will not start their trip until after their follower arrives at the terminal. If that standing bus is non-operational or undesirable, and the driver pulls out and starts his trip with the bus that his follower pulled in with, it is called jumping buses. That follower can then pull out with the bus of his follower, and so on allowing trips to proceed as scheduled even if one bus 1 is disabled. Of course, it effectively reduces recovery time by the headway of the route. As jumping buses is limited to one location, only one order needs to be given, which can then be passed on from one operator to the next.

4.2.3 Managing Reliefs (R)

R.1 Wait for Relief

If a relief operator is not present at a relief point, the easiest response can be for the operator being relieved is simply to wait and see if the relief driver shows up soon. This of course means there is no service until the relief appears, which can seriously inconvenience any passengers already on the bus, but it avoids much of the complication associated with juggling reliefs.

R.2 Relief Operator Relieves Other Than Scheduled Operator

In this case, a relief operator relieves a different operator than he normally does. This can never occur singly in isolation, but can be combined with itself or pull in (R.4.)

R.3 Relief Operator Relieves Scheduled Operator Later

In this case, a relief operator scheduled to make a relief of a certain driver at a certain place and a certain time, makes the same relief of the same driver at the same place at a later time, a half trip or round trip later. The driver is usually given overtime pay for his extra work.

R.4 Pull In

In this case a driver returns his bus to the garage at a time when he would normally be relieved or in the case of mechanical defects, continue in service. For reliefs it is often accompanied with a "pull out instead of relieve," below.

R.5 Pull-out Instead of Relieve

In this case, a relief operator who would normally make a relief at a relief point starts a trip at a garage instead. This works best if the driver to relieve has pulled in, above, and the relief point is fairly close to the garage.

R.6 Operator Exchange

When "juggling reliefs," as the application of some of the above is called, an agency can end up with all their trips filled but some of them filled with different drivers than usual. Sometimes the drivers can just remain on their new runs, but they can also be scheduled to work for different lengths of time, scheduled to make reliefs, scheduled to take different routes later on, etc. In these cases it is sometimes necessary for operators to meet in the middle of a route, cross the street to the other bus, and resume their regular route. This is an operator exchange. Along busier streets, it is usually necessary to determine the location ahead of time in order to idle at designated stops and cross the street at designated crosswalks. Along streets with light traffic it can sometimes be easier just to trade buses when they make visual contact.

4.2.4 Providing Additional or Altered Service (A)

A.1 Use Standby Bus

Some transit agencies will have a standby or "Run As Directed (RAD)" bus and driver ready to quickly take the place of a run that is not in service for any reason, or provide extra service where it is needed. There are many different uses of standby buses, including providing extra service for a crowded route, replacing a bus with a mechanical defect, etc. which for our purposes we will lump together. The operator of the standby bus needs to know where to go, what to do on arrival, and possibly an entire run schedule and driving directions. Before someone makes a decision to use a standby bus, that person must first know whether the bus is already in use.

A.2 Fill from Another Street

This refers to taking a bus and driver normally operating on one route and placing it on another. This is most frequently used to make sure that an departure on a long-headway route is not missed, at the expense of crowding on a short-headway route. It can also be used to balance crowding on a number of routes.

A.3 Fill with Pull-in

Another way to provide replacement or additional service is to use a bus and driver that were originally scheduled to pull in. This usually involves the expense of overtime pay.

A.4 Put Bus in Place

If a bus is beginning its run late or is going back in service after an absence, it is necessary to determine where the bus should resume its service. This decision is complicated by modifications that have been made to the route's schedule to compensate for the bus' absence, reliefs the operator is involved in later in the day, etc.

A.5 Emergency reroute

If bus operators are required en masse to operate along a different route than they are used to, they must all be given instructions on how to proceed along their new route. Adjustments to the schedule, or the creation of an entirely new schedule, may also be necessary.

4.2.5 Dealing with Emergencies (E)

E.1 Bus Continues to Point Supervision

In some emergencies, the bus can safely continue to the nearest point supervisor, who can deal with the situation. For this to happen effectively, the bus operator may need to be instructed to proceed, and the point supervisor should be notified to ensure that he is there and prepared to assist when the bus reaches him.

E.2 Dispatch Mobile Supervision

At times it is necessary to dispatch mobile supervision to deal with an emergency, either to a fixed point or to intercept a bus in motion. To do so the mobile supervisor needs to know the nature of the emergency, the location of the bus, and if the bus is moving, enough information to locate it successfully (either knowledge of the bus' route and the time corresponding to the given location, or real-time tracking.)

E.3 Dispatch Police and / or Medics

If police or medics are necessary, the police department or 911 dispatching center must be informed of the nature of the emergency and the bus' location. If a bus is moving, it would be necessary to give the police department enough information to locate the bus, which would involve a greater degree of communication than when dispatching mobile supervision above because the police are likely to have less knowledge of agency bus routes on hand than a mobile supervisor.

4.3 Information Needs in Disruption Management

In this section, we will study the information requirements of understanding the occurrence of disruptions, choosing the most appropriate response technique, and implementing that technique. Note that the examples we will review are generalized. Some rarely used responses are omitted, and some charts will vary greatly by agency. These charts are intended as a general, rather than an exhaustive, framework. Table 4-2 summarizes the relationship between responses and disruptions.

4.3.1 Chart Format

Symbols

Problem impacting one bus specifically, such as a breakdown

Problem impacting a bus route in general, such as congestion

Knowledge that does not change often, such as the schedule of a bus

Information that changes continually, such as the location of a bus

An actor such as a bus driver

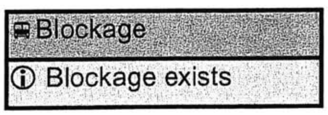
Table 4-2: Disruptions and Responses		
1	Bus early	Hold bus (H1)
2	Bus delay (short headway)	Hold leader (H2), drop off only (H3), expressing (H4, H5), short turn (H6), follower picks up passengers (H7)
3	Bus delay (long headway)	Drop off only (H3), expressing (H4, H5), short turn (H6), follower picks up passengers (H7)
4	Crush load	Hold leader (H2), drop off only (H3), use standby bus (A1)
5	Mechanical problem, minor	Repair at terminal (M1), jump buses (M7), juggle reliefs (R1-6)
6	Mechanical problem, serious	Repair bus (M1-3), bring bus change (M4), jump buses (M7), juggle reliefs (R1-6), use standby (A1)
7	Mechanical problem, major	Repair bus (M1-3), bring bus change (M4), tow bus (M5), jump buses (M7), juggle reliefs (R1-6)
8	Emergency	Continue to point supervision (E1), dispatch mobile supervision (E2), dispatch police / medics (E3)
9	Accident	Dispatch mobile supervision (E2), dispatch police / medics (E3)
10	Operator misses relief	Juggle reliefs (R1-6)
11	Blockage	Emergency reroute (A5)
12	Bus standing / Service gap	Follower picks up passengers (H7), spread the interval (H8), spread the terminal (H9)
13	Unfilled run	Use standby bus (A1), fill from another street (A2), fill with pull-in (A3)
14	Unplanned bus bridge	Use standby bus (A1), fill from another street (A2), fill with pull-in (A3), pull out instead of relieve (R5), emergency reroute (A5)
15	Congestion / Weather	Spread the terminal (H8), use standby bus (A1), fill from another street (A2), fill with pull-in (A3)
16	Late pull-out	Put bus in place (A4), stop spreading the terminal (H8)

An action or intervention to improve service, such as expressing a bus

A "necessary" action, such as towing a disabled bus

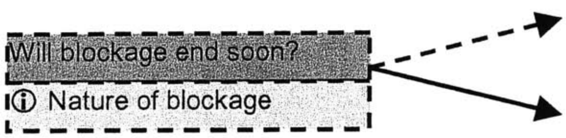
① The first (second, third…) choice among several similar recovery techniques

Shapes



First block – nature of problem

Following blocks – information required to know of problem

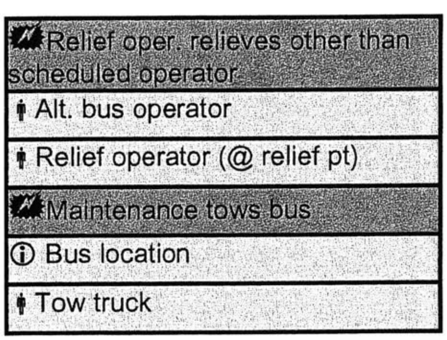


First block – a question, the answer to which determines the next action

Second block –knowledge or information needed to answer the above question

Dashed line – Points to a possible decision stemming from the question

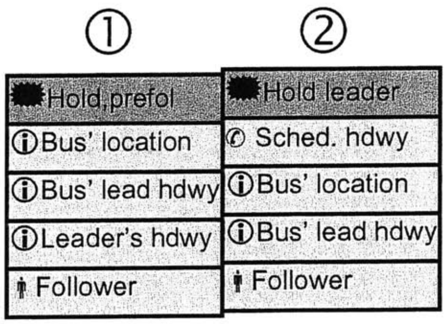
Solid line – Points to a "default" choice if there is not enough information to answer the relevant question



Second and third blocks – knowledge, information or actors required to execute the action indicated in block one

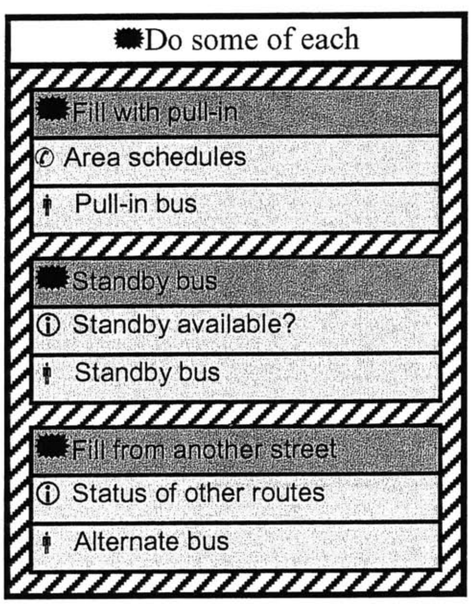
Fourth block – action which accompanies the action indicated in block one

Fifth and sixth blocks – knowledge, information or actors required to execute the action indicated in block 4



Left hand blocks (marked "1") – preferred version of two similar actions

Right hand blocks (marked "2") – less preferred version of two similar actions

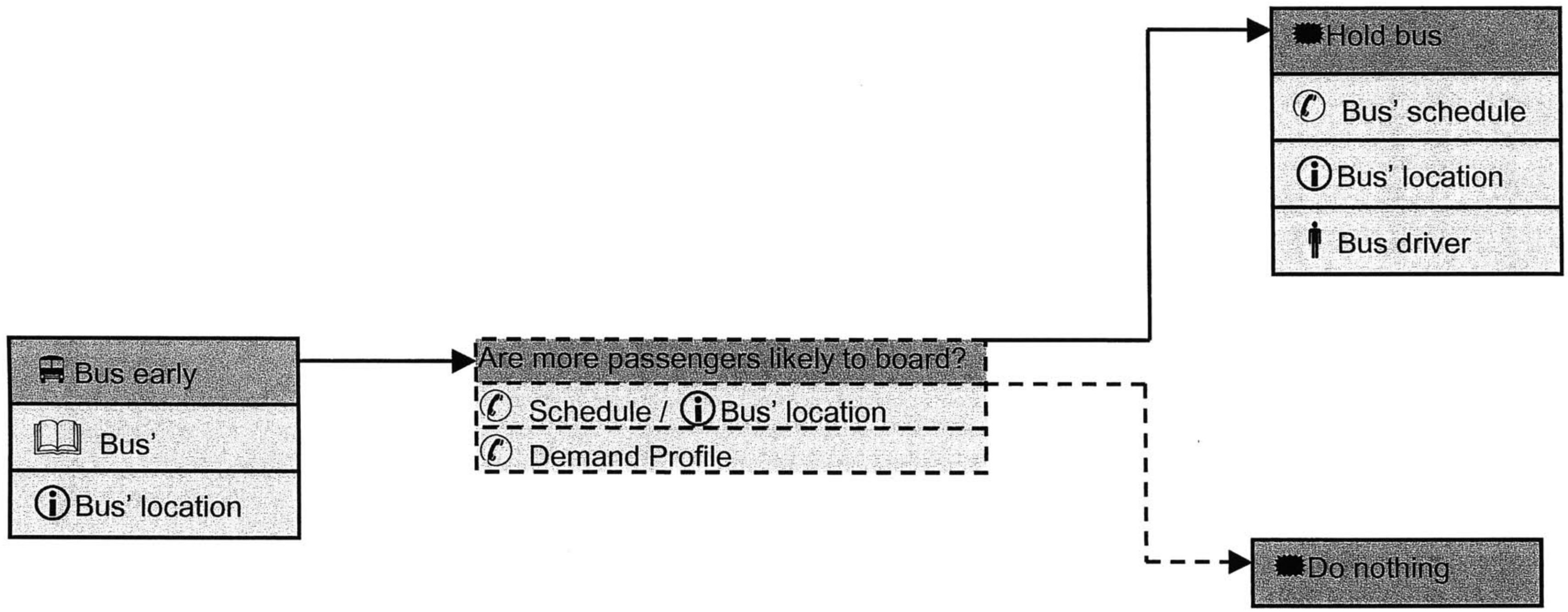


Striped box – Indicates a set of actions, each of which should be considered

4.3.2 Bus Early (Figure 4-1)

While preventing buses from being early may seem to be a trivial problem, it is a problem that exists, and it serves as a good introduction to this set of charts.

Figure 4-1: Bus Early



On the left of the diagram is the problem: a bus is early. To be aware that a bus is early one must know both the bus' schedule – where it is supposed to be – and the bus' location, where the bus actually is.

Following the arrow to the center blocks, we come to the only question that must be asked in order to deal with this problem effectively. It makes sense to hold a bus only if more people are expected to board. If they will board, then they run the risk of missing the bus if it arrives early. However, if the bus is nearing the end of its trip, it may only be distributing passengers already on board. Therefore, to choose an appropriate response, one must know the bus' location (or roughly where it should be) and where people typically board.

Based on this, the solution to the problem is either to hold the bus – an action that requires knowledge of the bus schedule and location, so that the bus can be held for the appropriate length of time, and an action by the bus driver – or the solution is to do nothing. Holding the bus is the "default" solution. If no one is in a position to decide whether letting the bus stay ahead of schedule would be damaging, then the bus should be held to ensure that passengers who arrive on time do not miss the bus.

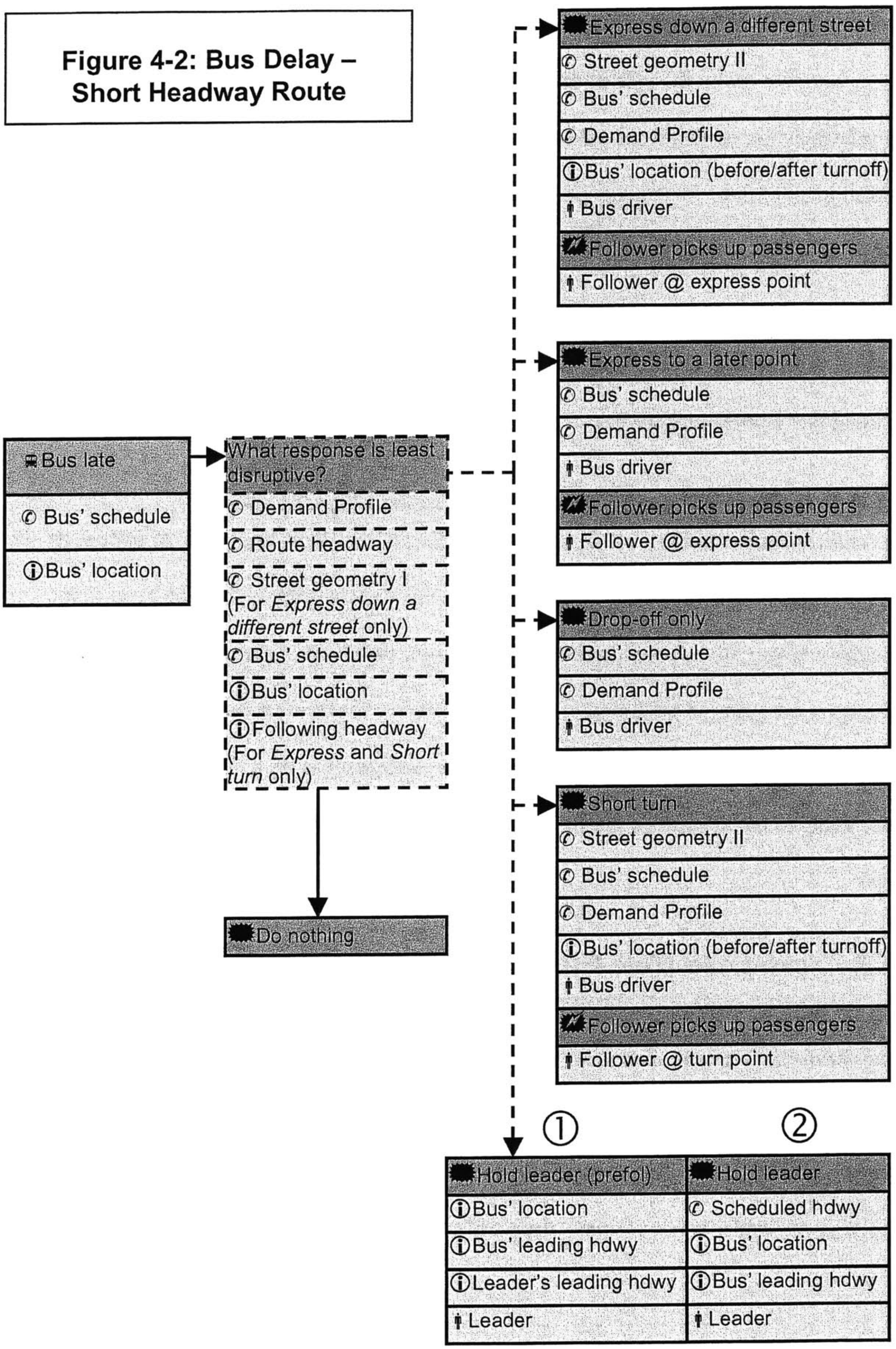
While the purpose of these charts is not to determine the optimum role of responsibilities chart-by-chart, in this one instance it is useful to see where that would take us. The bus driver is the only actor here, and he already knows the necessary information to hold the bus. As this is the default of the two choices, one option is to have the bus operator always hold the bus if he is ahead of schedule. This ensures that passengers who arrive on time will be able to board, so it solves the main problem, but it may also create some unnecessary delay if the bus is held near the end of its route. If a bus driver knows where customers typically board, another option is to give him the power to make the holding decision or not. While this is an elegant solution it means giving the driver a great deal of discretion, and can have negative consequences. Allowing the driver to make this choice may occasionally reduce the cost that would be caused by unnecessary waiting, but it could also create the significant cost of a passenger missing his bus because of an operator's lapse in judgment. One solution would be to give the authority to someone else who knows the schedule and the demand, the scheduler, who could note portions of the route for which holding is unnecessary. Another would be to place supervisors in charge of holding, but this is a step back as the bus would only be held at points with supervisors. Incorporating the information in the schedule is the most elegant solution.

4.3.3 Bus Delay – Short Headway Route (Figure 4-2)

Here we see that in order to know that a bus is late, one must know the bus' schedule and location.

Whether it is appropriate to express the bus, have it drop off passengers only, short turn, hold its leader or do nothing depends on the above information, the following headway, the route's schedule and its demand. To know whether expressing a bus down a different route is a time-saving option, a basic knowledge of street geometry is required as well. The bus' following headway is important to decisions on expressing, short turning and running as drop off only because it denotes the length of additional time passengers who would have boarded the bus will have to wait, and it is particularly important for expressing and short turning, for which the cost also applies to passengers forced to disembark. "Do nothing" is the default response because without this fundamental

Figure 4-2: Bus Delay – Short Headway Route



knowledge, a decision-maker is liable to make things worse with an intervention, and would therefore err on the side of caution and let the bus be late. As short-turning a bus is particularly disruptive, it should only be considered if a bus will start its next trip late without intervention. In the case of short-turning or expressing it is essential that the following bus allow free boarding to any passengers that were forced to disembark. Depending on an agency's fare system, this may or may not require that the follower be notified. Even if it does, it must be notified only when it reaches the point of expressing, meaning that a point supervisor can manage both parts of this operation.

4.3.4 Bus Delay – Long Headway Route (Figure 4-3)

This chart is similar to Figure 4-2, although holding the leader is no longer an option, as it is not likely to help on a long headway route. Most noteworthy is that one must first consider whether the bus is bunched, and if it is not, simply let it complete its trip. If passengers are going to be forced to wait forty minutes for the next bus, the overall effect of expressing is going to be highly negative. As a delayed bus on a long-headway route is not likely to be bunched in the first place, interventions are unlikely for long-headway routes.

4.3.5 Crush Load (One Bus - Not Delayed) (Figure 4-4)

In dealing with a crush load, the most important distinction is the frequency of the route. If the service is frequent, then those unable to board a bus experience a delay waiting for the next one. In this case the usual favored response is to hold the bus' leader, in order to have less passengers waiting to board the bus at future stops, ameliorating its crowding. If holding the leader is not possible, drop-off only has some appeal; those who are passed

Figure 4-3: Bus Delay – Long Headway Route

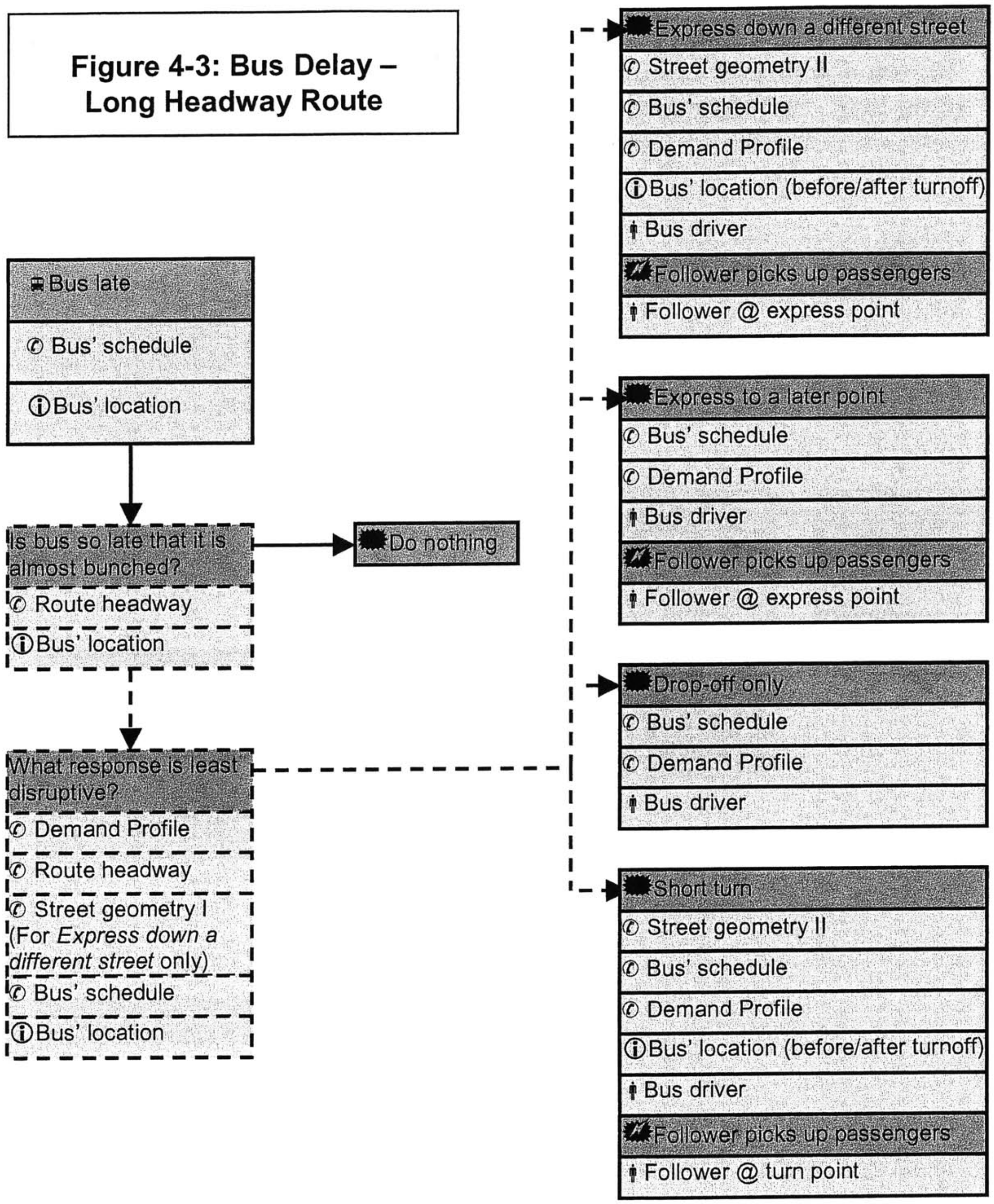
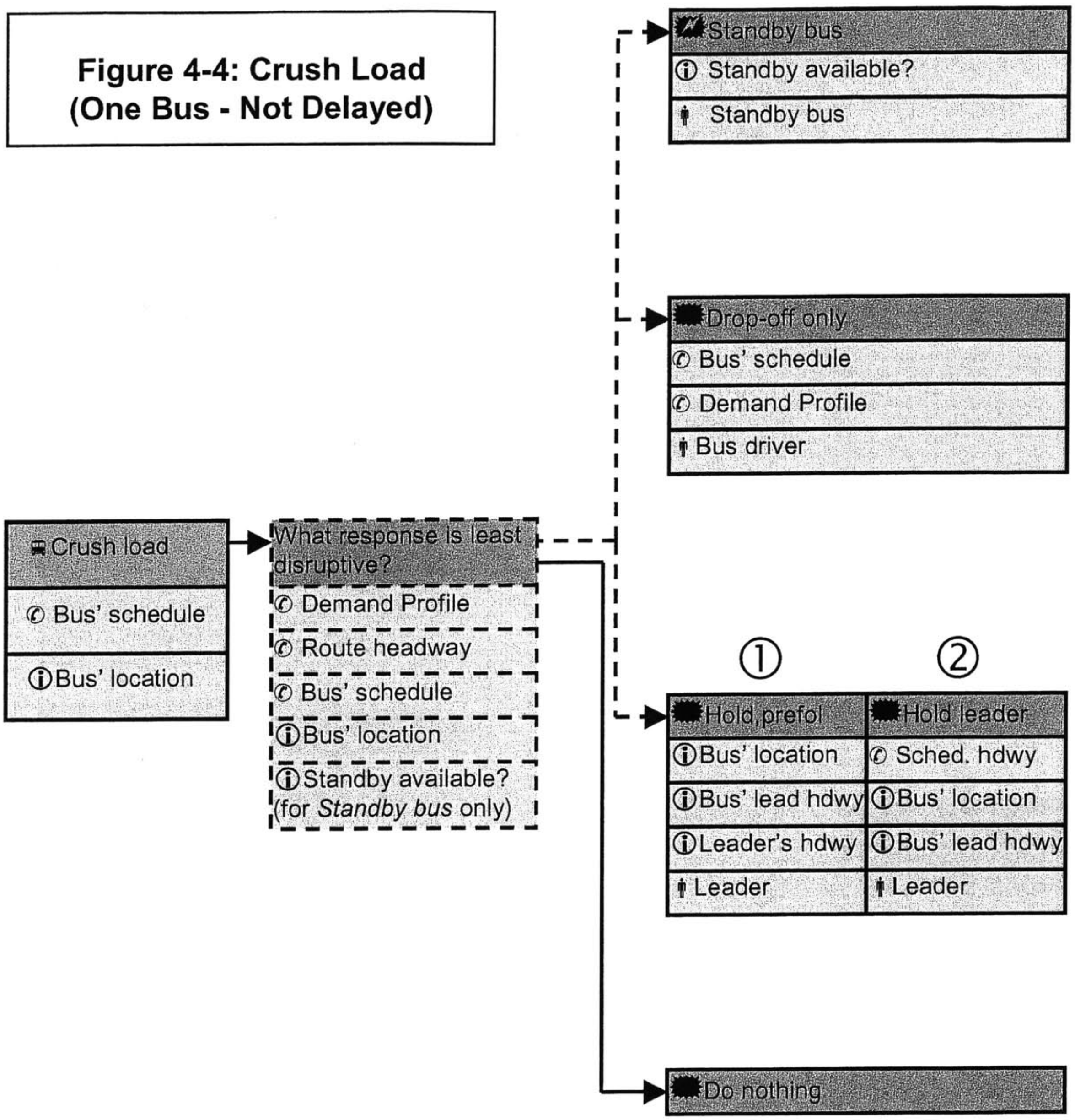


Figure 4-4: Crush Load
(One Bus - Not Delayed)



by the bus might not be able to board it anyway due to the crowding, so this would help the bus return to a normal load and stay on schedule.

If headways are very large, customers are effectively being denied service altogether. In this case, it is necessary to try to bring a bus in from somewhere else, most likely a standby bus. A standby bus is also an option for short-headway routes, but it is less likely to be the best use of that bus.

4.3.6 Mechanical Problem (Minor - Bus Movable) (Figure 4-5)

In dealing with a mechanical defect that does not take a bus out of service, the objective must be to fix the defect if it is possible to do so without disrupting service, and to fix the defect using as little of an agency's resources as possible. Calling a repair truck or ordering a bus change is not usually a viable option, as maintenance's resources need to be reserved for repairing buses that are out of service. Repairing the defect on-site with a supervisor partway through the route may be advisable, depending on the severity of the problem and the likely difficulty of repair, but may be inadvisable due to the delay to the bus and its passengers during the repair. That leaves having a supervisor repair a defect at the terminal, the best option, or a number of options for taking the bus out of service without missing any trips.

4.3.7 Mechanical Problem (Serious - Bus Movable without Passengers) (Figure 4-6)

If a bus cannot carry passengers, it should be removed from service if possible. Two ways to do this are juggling reliefs and using a standby bus. In the case of a standby bus, the driver of the disabled bus would meet the driver of the standby bus, they would

Figure 4-5: Mechanical Problem (Minor - Bus Movable)

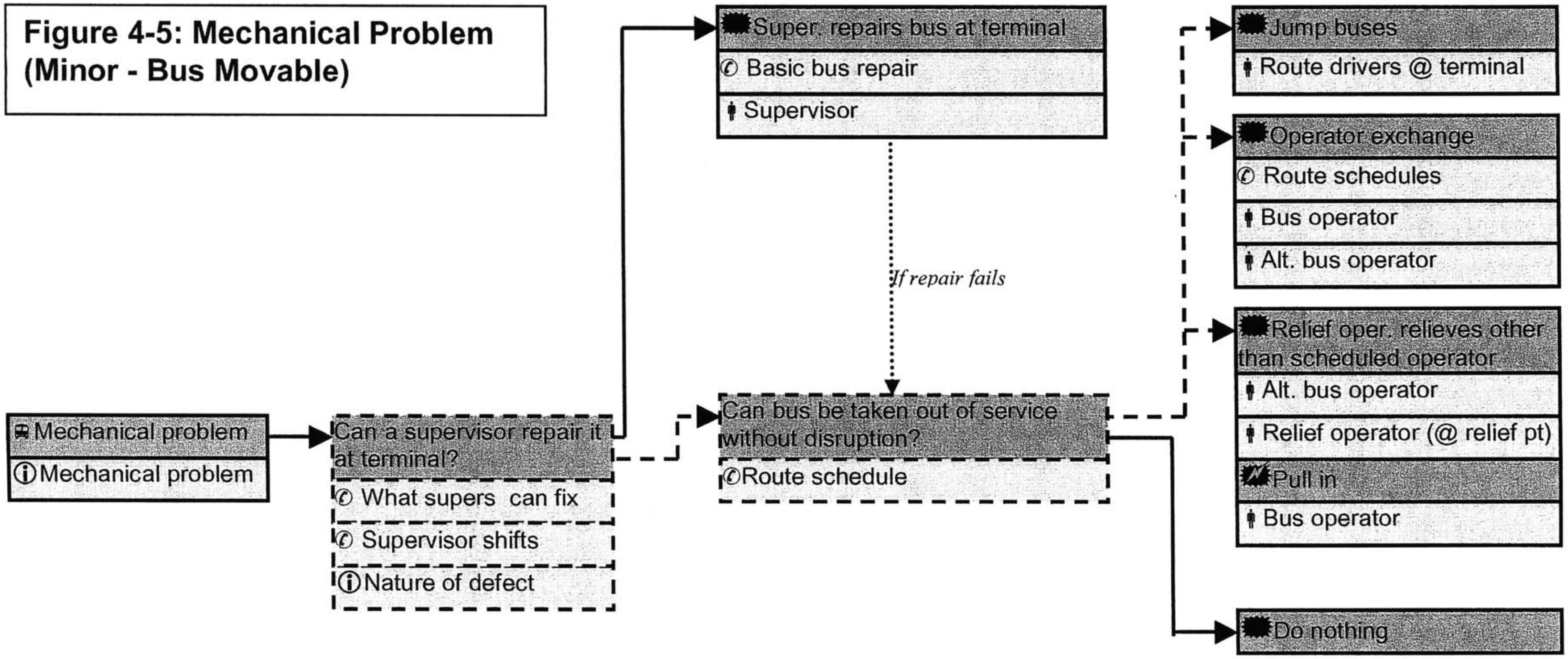
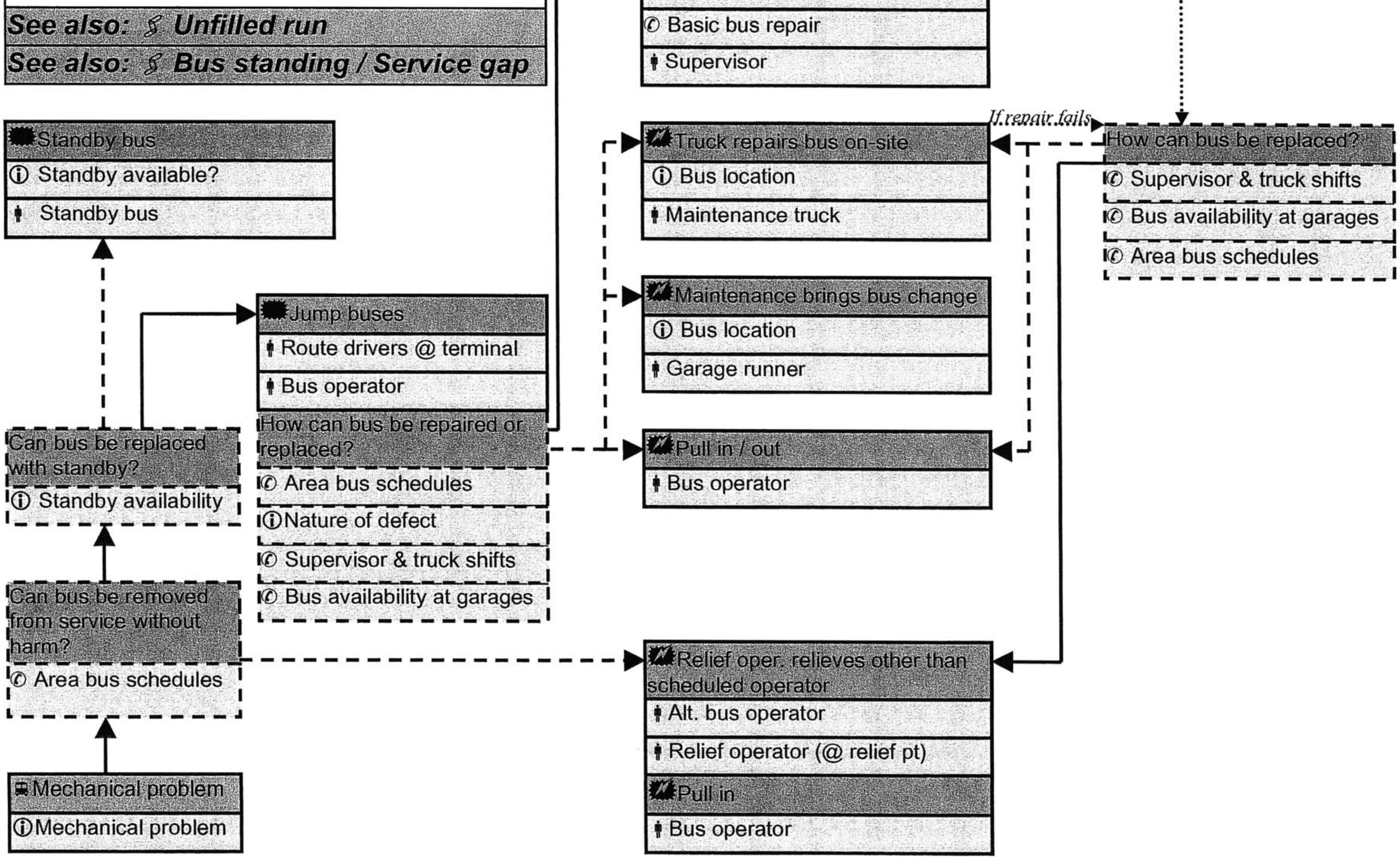


Figure 4-6: Mechanical Problem (Serious - Bus Movable w/o Passengers)



exchange buses, and the driver of the standby bus would pull in and out. In either of these cases the bus is removed from service with very little disruption. If neither one is possible, then jumping buses can prevent the breakdown from impacting additional passengers for the time being. The bus would of course have to make it to a terminal for jumping buses to be an option. If buses are being jumped, then a supervisor or a repair truck can attempt a repair, or maintenance can bring a bus change. The driver can also pull in and out, although this is incompatible with jumping buses and leaves a run without service for the time taken to perform the activity.

An attempt to repair the bus may fail, in which case the same decision must be made again, but with a smaller number of options. Juggling reliefs should be re-examined as time has passed since before the repair attempt.

4.3.8 Mechanical Problem (Major - Bus Immobilized) (Figure 4-7)

If the bus happens to have failed at a terminal, then jumping buses should be instituted. Other than that, the bus' immobility has reduced the possible choices from the previous problem. It can only be repaired on-site or towed, and towing may be accompanied by either a bus change brought by maintenance or an alteration to the relief schedule. Towing can also occur by itself, in which case the run will remain unfilled for its duration.

4.3.9 Emergency / Security / Fare dispute (Figure 4-8)

Emergency, security and fare dispute issues require an agency presence of higher authority than a bus driver, such as a mobile or point street supervisor. They often require police or even medical personnel. Fare disputes can usually be dealt with without outside help, but one cannot assume that this will be the case.

Figure 4-7: Mechanical Problem (Major - Bus Immobilized)

See also: Unfilled run

See also: Bus standing / Service gap

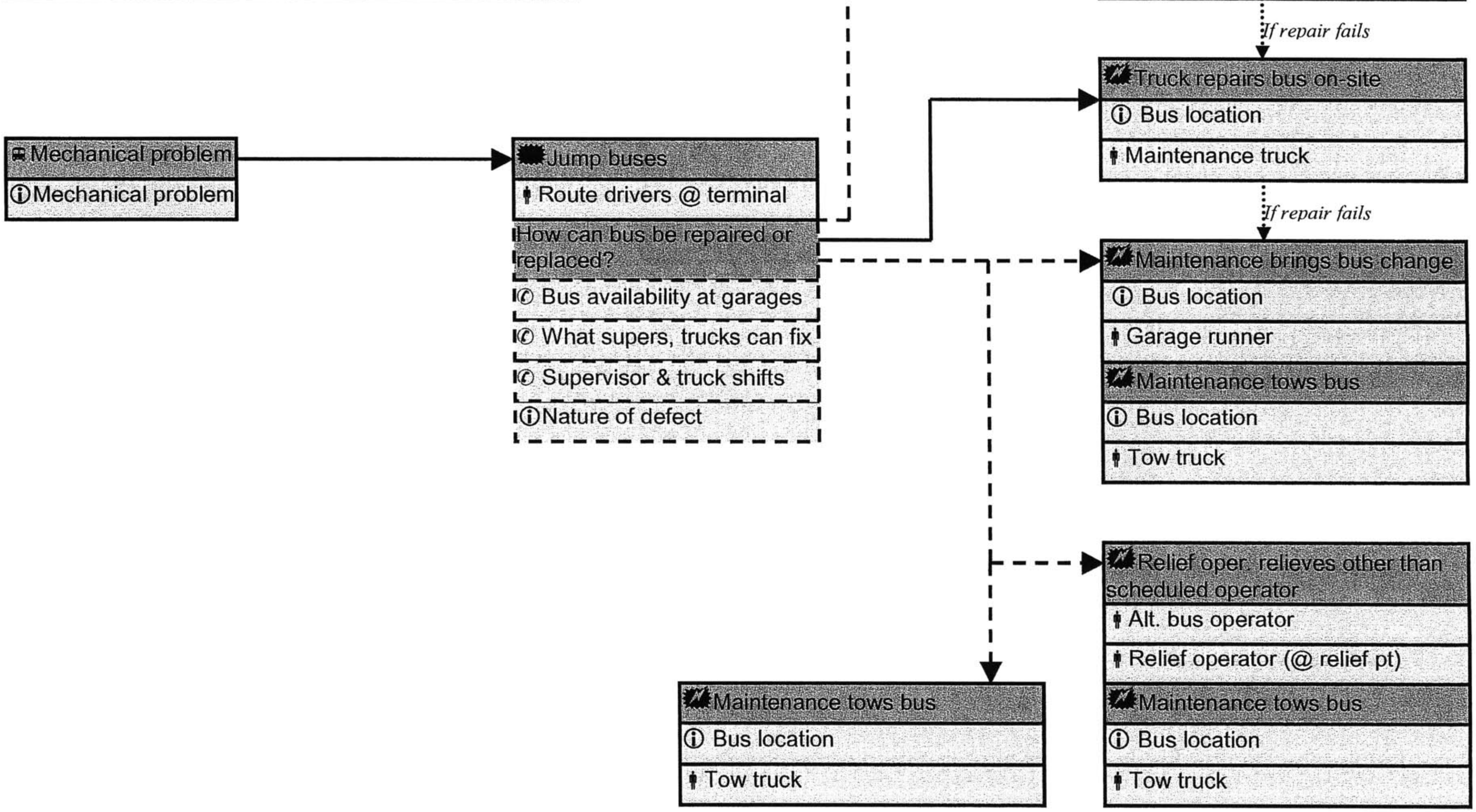
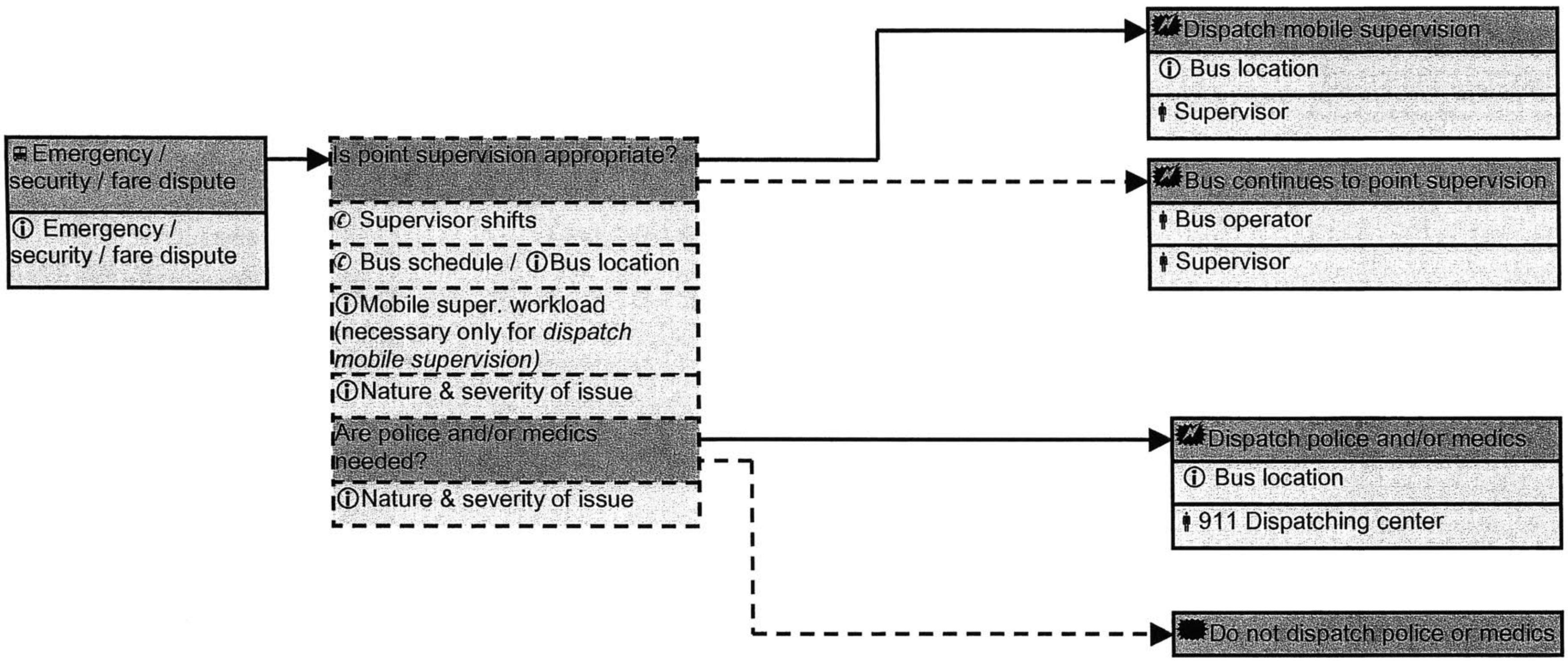


Figure 4-8: Emergency / Security / Fare dispute

See also: Bus delay



4.3.10 Accident (Figure 4-9)

The only distinction between accidents and emergencies is that accidents necessarily involve the police and result in mechanical defects. Note that an accident that occurred within a garage, such as one bus brushing another during a pull-out, would not qualify as an "accident" under this definition, but as an internal garage issue, potentially resulting in an unfilled run (4.3.14).

4.3.11 Operator Misses Relief (Figure 4-10)

In dealing with an early bus, the appropriate response is obvious and consistent, but in dealing with a missed relief, the possible responses are many and vary greatly from agency to agency. This chart represents one possible course, designed to show a maximum of potential responses.

If possible, operators should start jumping reliefs immediately, in order to prevent or minimize any absence in service. In this chart, the agency is shown ordering the bus to continue in service and juggle reliefs later if jumping reliefs is not possible and there are passengers on the bus in the middle of their trip. Of course, this policy may vary greatly from agency to agency, ranging from continuing in service even if it means starting a new trip on a high-frequency route, to standing the bus even if it is standing room only. Similarly, this chart shows both juggling reliefs with and without a pull-in, and pulling in and letting the relieving driver pull out late; the various merit of these varies greatly according to agency policy and operating environment.

Figure 4-9: Accident

See also: Mechanical problem (major)

See also: Unfilled run

See also: Bus standing / Service gap

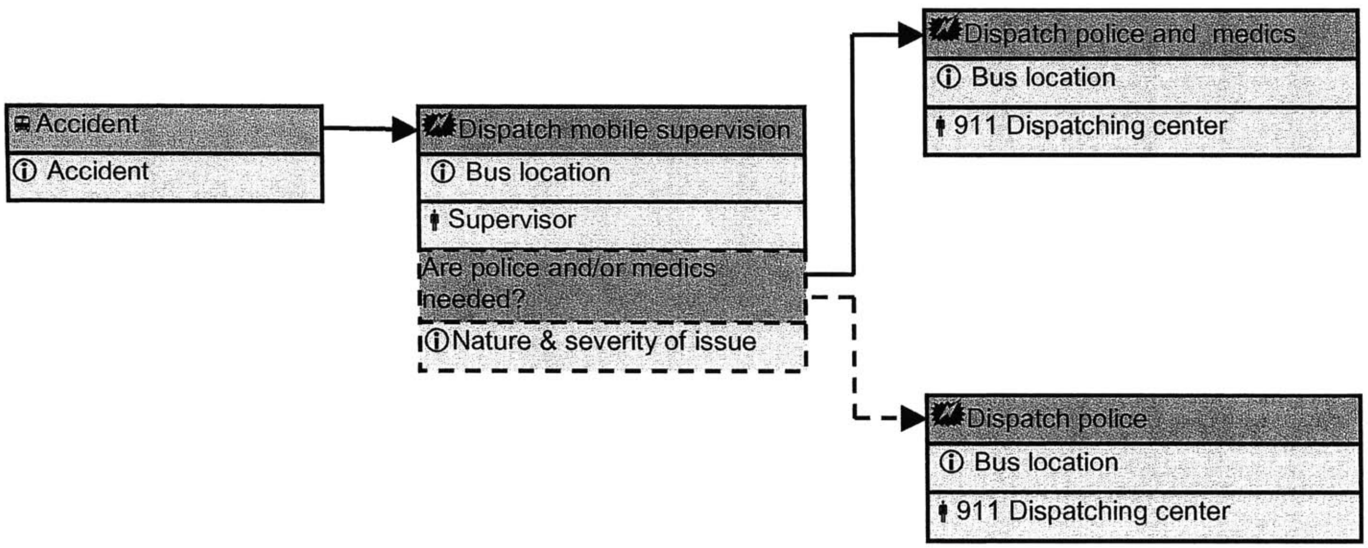
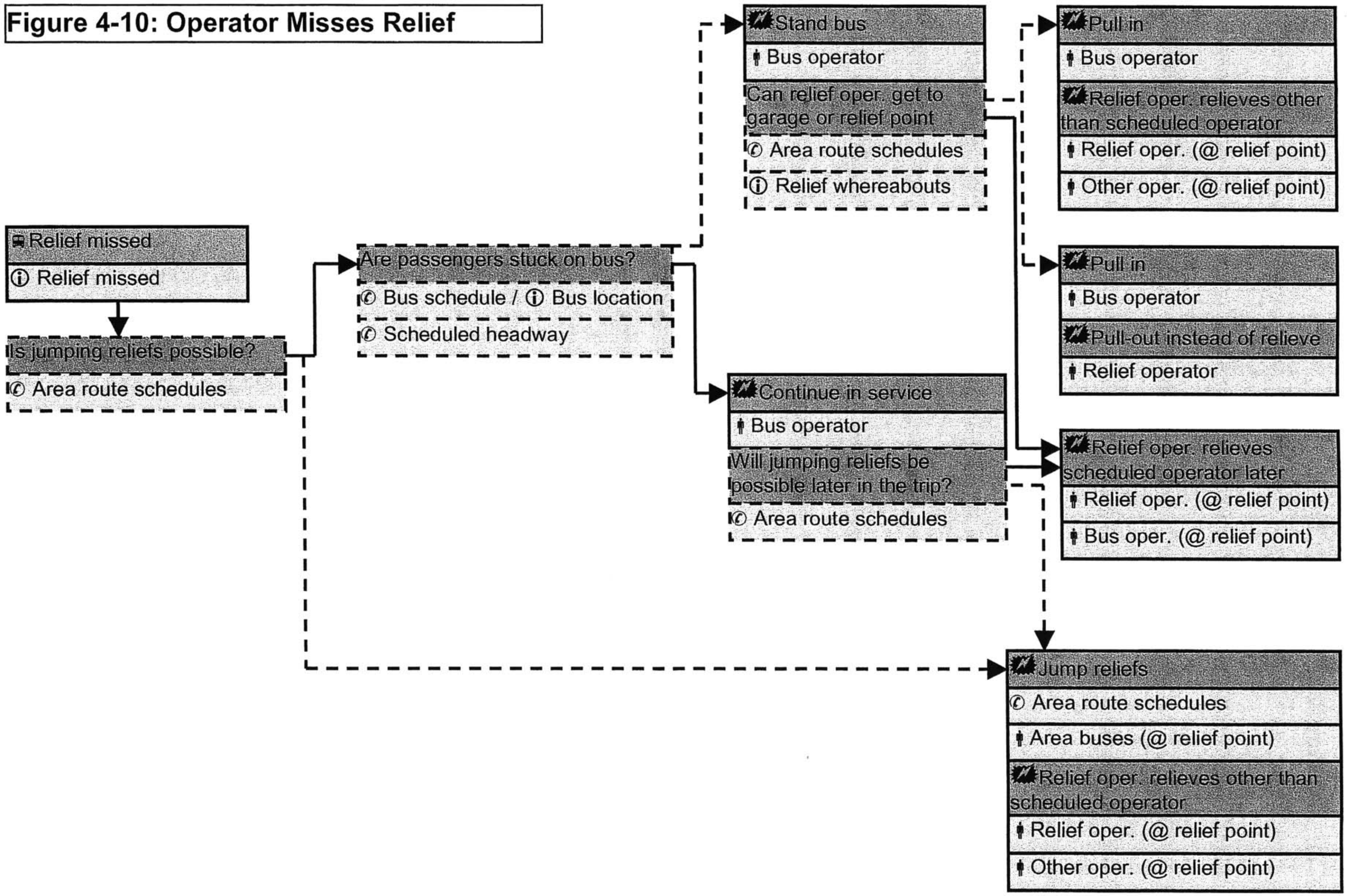


Figure 4-10: Operator Misses Relief



4.3.12 Blockage (Figure 4-11)

Some blockages, such as those resulting from auto accidents, may only last a short period of time. If such a prediction can be made, then rerouting buses may be more trouble than it is worth, and the blockage should be treated as a bus delay. If the blockage is expected to last a long period of time, or if this cannot be reasonably determined, then rerouting is necessary.

If the reroute adds a significant amount of length to the route, then either the street must be re-spaced ("spread the terminal," also known as "reschedule the street") or buses must be added to the route. This is analogous to Unfilled run (4.3.14), even though there is not technically a run that is unfilled. Under severe circumstances it may be analogous to a number of unfilled runs.

4.3.13 Bus Standing / Service Gap (Figure 4-12)

A note should be made about the relationship of *Bus standing / Service Gap* to *Unfilled run* (4.3.14.) These represent two conditions that commonly occur together. Bus standing / service gap represents an immediate absence of service, and how to run the route effectively without that service until it is returned. Unfilled run refers to the absence of both a bus and a driver, and the attempts to restore service providing both. An accident in which the driver is removed from service and the bus is damaged would create both an unfilled run and a service gap. A serious mechanical defect would create a service gap, but not an unfilled run, as there is a driver available, but no bus, necessitating a different set of restorative techniques.

Figure 4-11: Blockage
See also: Bus delay

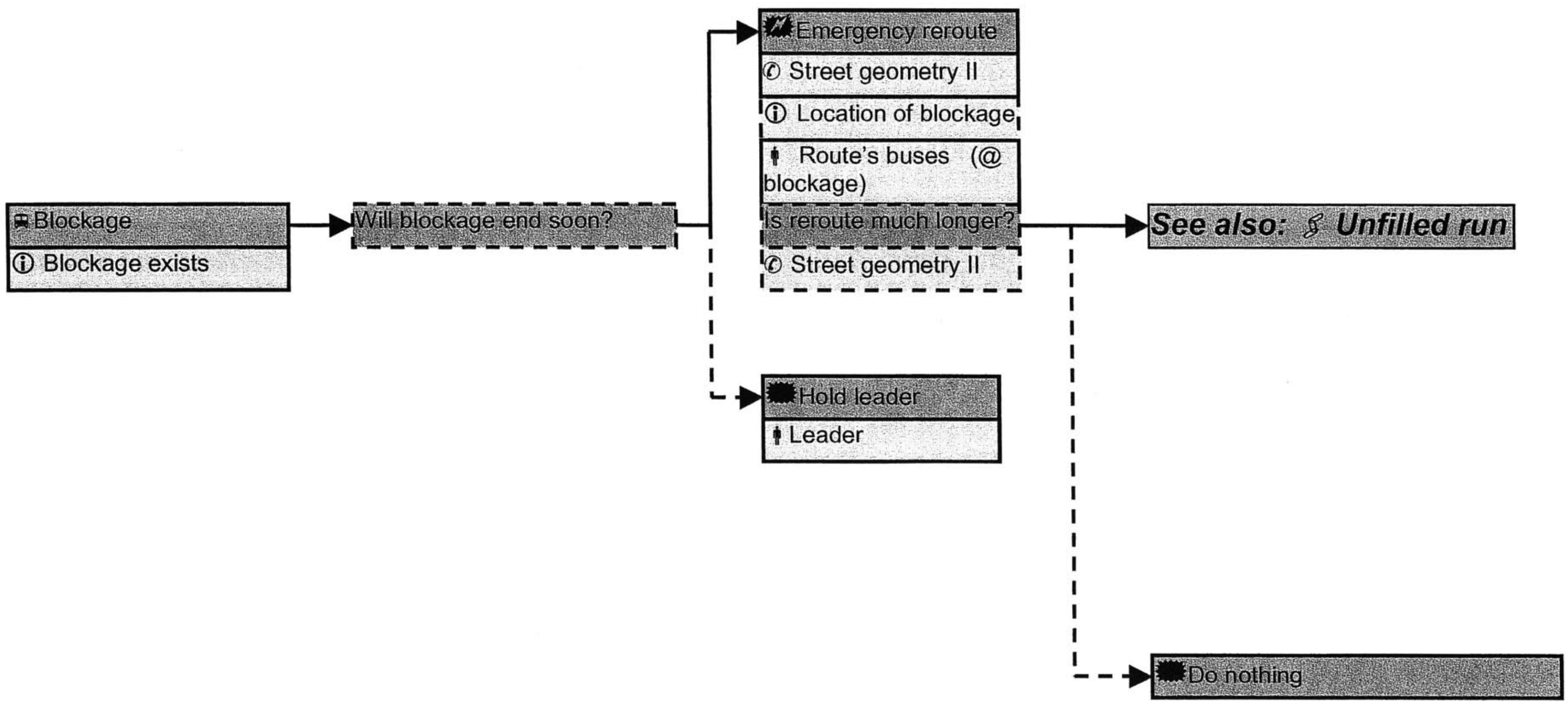
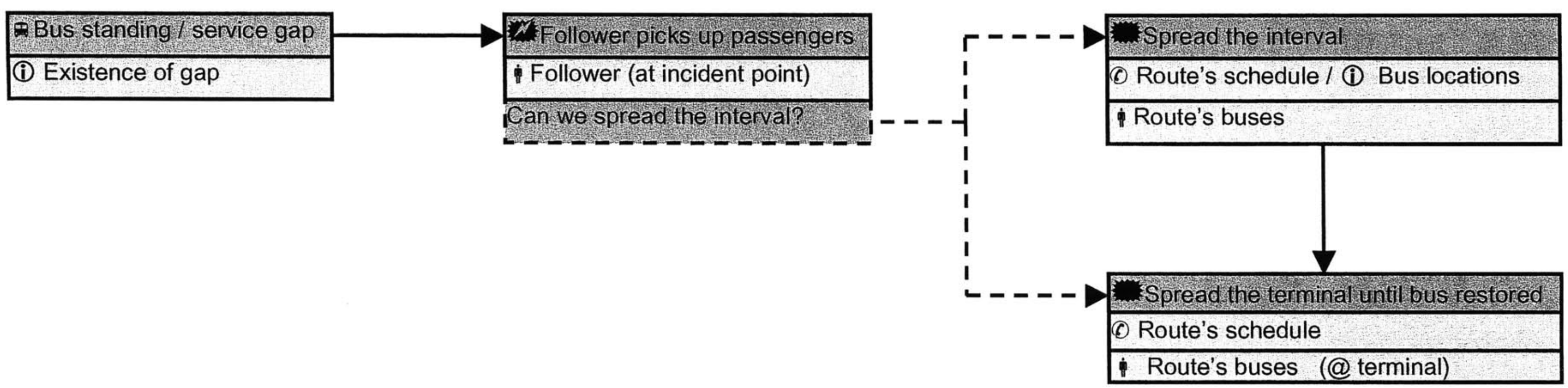


Figure 4-12: Bus Standing / Service Gap



With this understood, the chart is fairly self-explanatory. Any stranded passengers must be picked up free of charge by the follower, which might require an action on the follower's part or might happen automatically, depending on the agency's fare system and transfer policy. Spreading the interval should be done if the route is high-frequency and the agency has the communications capacity to do so, and spreading the terminal is required as well.

4.3.14 Unfilled Run (Figure 4-13)

(See also *Bus standing / service gap,* above, for a description of the distinction between it and *Unfilled* run.)

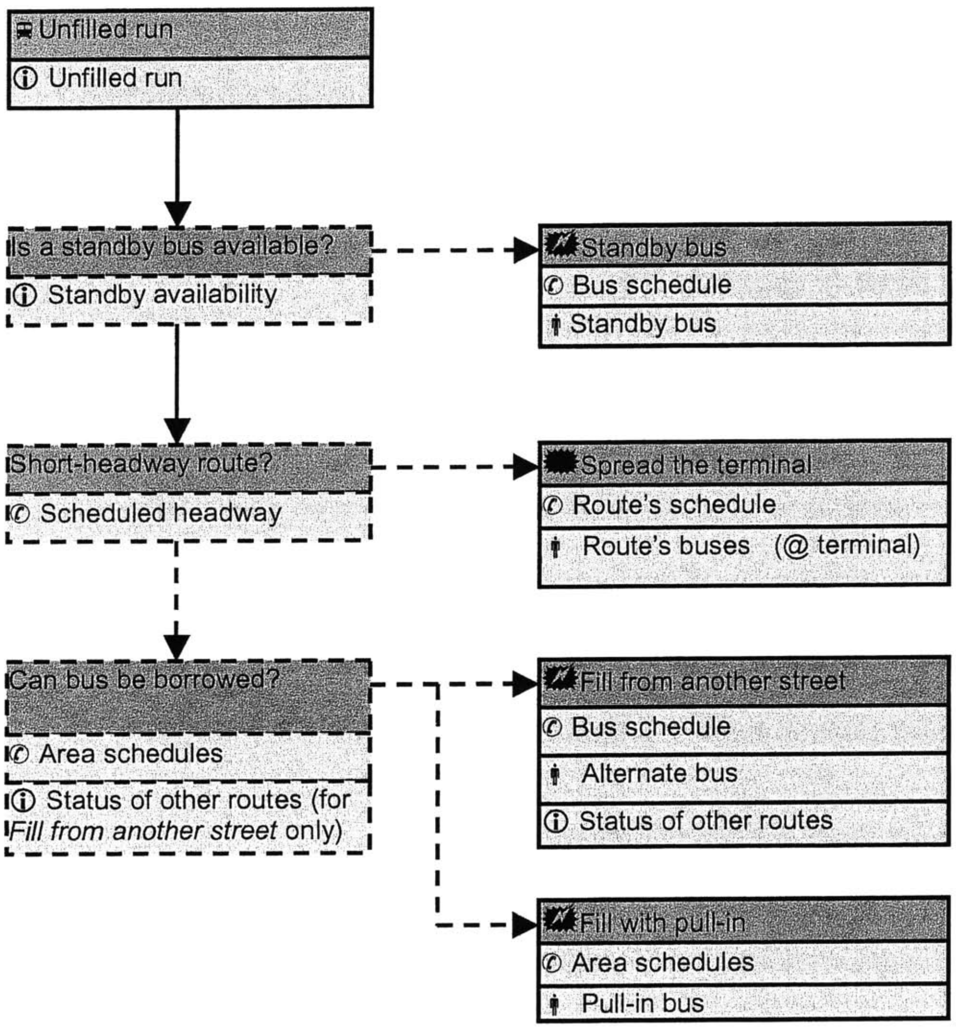
If a standby bus is available, then it should fill the run. If not, then the action taken depends on the headway of the route. If the route has a short headway, then it should make do by spreading the terminal. Only if the service is infrequent should the agency fill the run from another street or suffer overtime pay to avoid stranding passengers.

4.3.15 Unplanned Bus Bridge (Figure 4-14)

This condition is not unlike *Blockage* (4.3.12) but requires a greater number of buses and benefits greatly from a greater amount of oversight. Because of this, pulling out operators instead of relieving becomes an option, due to the greater number of buses that will be required. Also, due to the high volume of buses arriving at the route, the operators' unfamiliarity with the route itself, and the "improvisational" nature of the operation, the route can benefit disproportionately from a higher level of oversight in its early stages. Unfortunately, the information provided to someone operating on the route or supervising from a point along the route is much less than for a typical route, because they are not familiar with the patterns of the route or even its schedule.

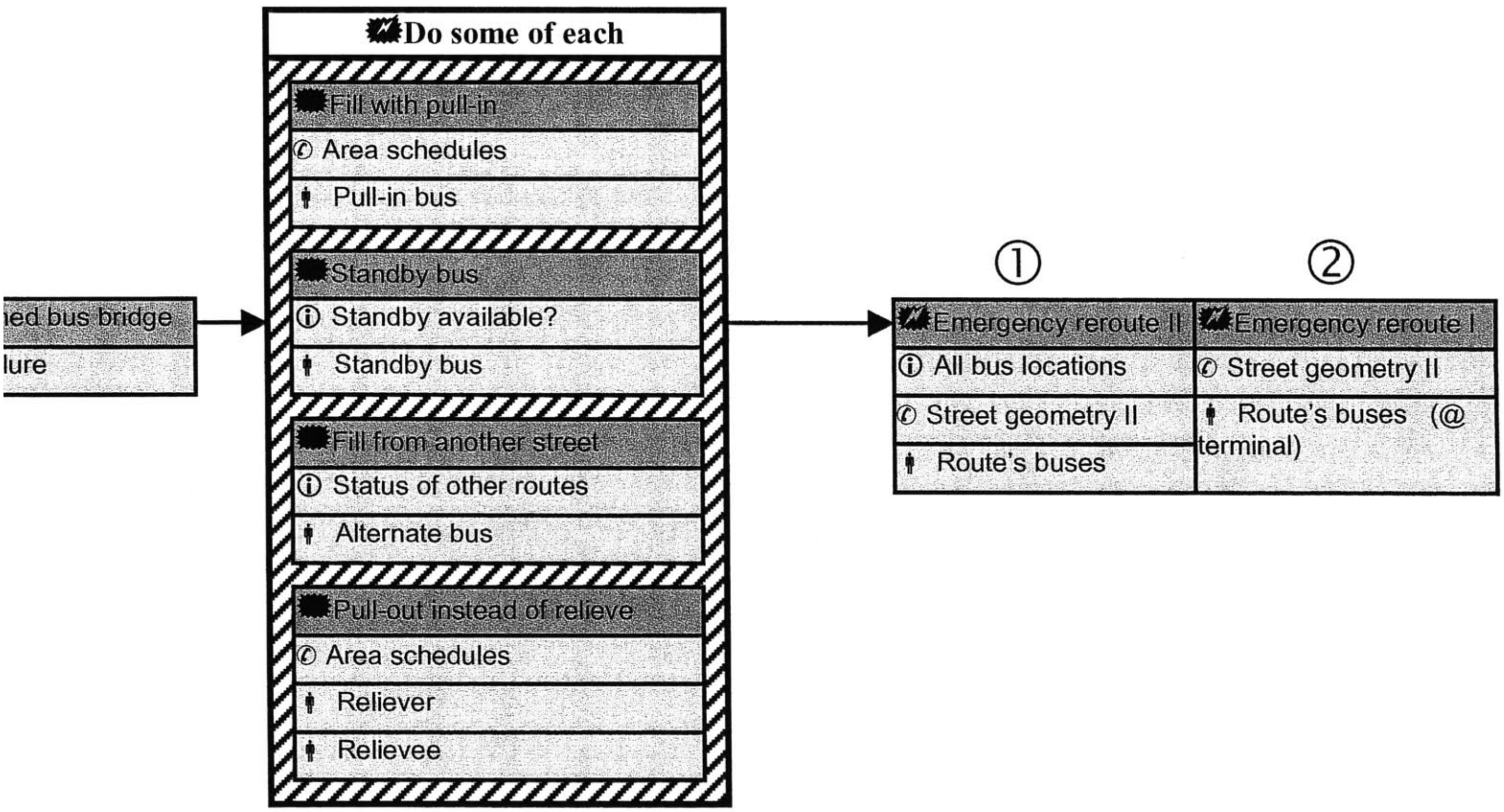
Figure 4-13: Unfilled Run

See also: Bus standing / service gap



4-14: Unplanned Bus Bridge

o: Unfilled run (many times over)



4.3.16 Congestion / Weather / Routewide Crowding (Figure 4-15)

This chart is also fairly self-explanatory. It should be noted that in the case of severe weather, it is not usually advisable to add a run from another route, as all the routes in the system are experiencing similar conditions.

4.3.17 Late Pull-out (Figure 4-16)

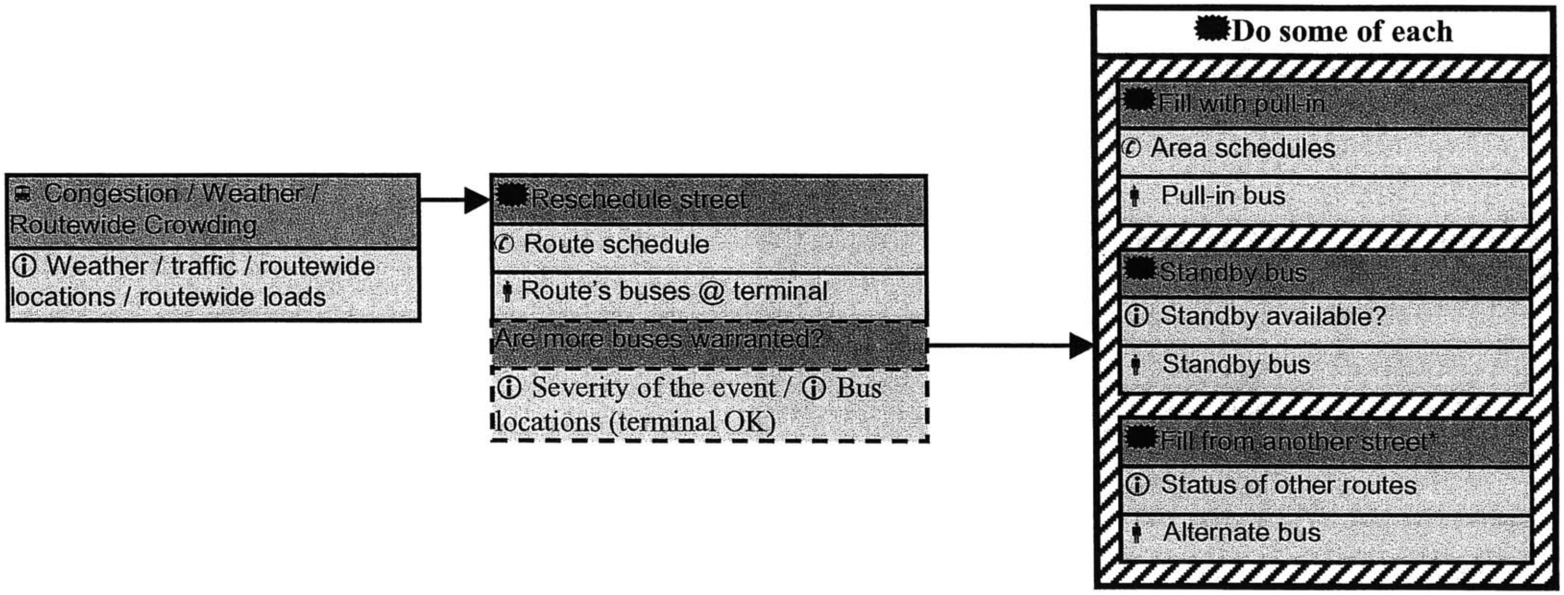
This item is unique within this list in that it represents the end of a problem rather than the onset of one. It is included because it does require certain actions to be performed, namely putting the bus in place and undoing the actions that had been taken to deal with the bus' absence. This usually means just stopping spreading the terminal, although if there has been a more complicated rearrangement of buses and drivers, then returning to normal operations may prove more complicated as well.

4.4 The Importance of Timeliness of Information

There are some situations in which information needs to be transmitted right away in order to be of use, and others in which it has a significant shelf life. An example of information with a long shelf life would be a broken heater on a bus. If it takes an extra ten minutes to relay the problem to a decision-maker, passengers will continue to ride without heat, but the problem will not escalate. An example of a situation in which a response needs to happen quickly is holding in response to bus delays.

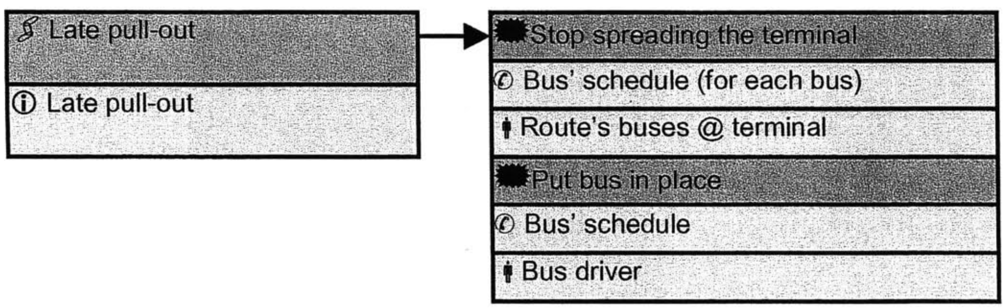
Let us study a simplified hypothetical route to demonstrate this phenomenon. Route X northbound operates on eight minute headways. It has 20 stops, each located two minutes apart, and each stop has the same demand of one passenger arriving every

Figure 5.15: Congestion / Weather / Routewide Crowding



* Fill from another street not applicable in case of severe weather.

Figure 4-16: Late Pull-out



minute. In our example, each passenger takes six seconds to board, and no time to exit. We will study three buses, A, B and C. Table 4-3 shows the times (starting from t=0) each bus reaches each stop if all three are on time throughout their trips. Each bus' scheduled arrival time, actual arrival time, waiting passengers wishing to board and departure time from the stop are also shown. For buses B and C, lateness compared to schedule and lateness compared to scheduled headway are shown at the end. Since the headways are consistent, there are always eight passengers waiting for each bus at each stop, and the dwell time at each stop is always 48 seconds (eight passengers times six seconds.)

In Table 4-4 we see what happens if bus C begins its trip two minutes late and there is no response. As one would expect, the increased number of passengers at each stop causes it to take longer at each stop, resulting in still more passengers waiting at the next stop and so forth. Assuming that bus C has a follower that remains on schedule, they will become bunched by stop 16.

In Table 4-5 we see what happens if bus B is held for one minute as soon as bus C makes its late departure, when bus B is at stop 5. (This length of holding time, like later lengths of holding time, was chosen to spread the delay between buses B and C as evenly as possible at trip's end.) Now both buses B and C finish their trip late, but neither is bunched, and by the end of their trips their headways are longer than scheduled by about the same amount: 3.8 and 3.6 minutes.

Now suppose it took ten minutes for a message to go out from bus C to a decision maker, for the decision maker to decide to hold bus B, and for the decision maker to inform bus

Figure 4-3: Information Timeliness Example: On-Time Operations

	Travel	Bus A				Bus B				Bus C				Lateness		Late. Head.	
Stop #	time to stop	Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	B	C	B	C
1	2.0	0.0	0.0	8.0	0.8	8.0	8.0	8.0	8.8	16.0	16.0	8.0	16.8	0.0	0.0	0.0	0.0
2	2.0	2.8	2.8	8.0	3.6	10.8	10.8	8.0	11.6	18.8	18.8	8.0	19.6	0.0	0.0	0.0	0.0
3	2.0	5.6	5.6	8.0	6.4	13.6	13.6	8.0	14.4	21.6	21.6	8.0	22.4	0.0	0.0	0.0	0.0
4	2.0	8.4	8.4	8.0	9.2	16.4	16.4	8.0	17.2	24.4	24.4	8.0	25.2	0.0	0.0	0.0	0.0
5	2.0	11.2	11.2	8.0	12.0	19.2	19.2	8.0	20.0	27.2	27.2	8.0	28.0	0.0	0.0	0.0	0.0
6	2.0	14.0	14.0	8.0	14.8	22.0	22.0	8.0	22.8	30.0	30.0	8.0	30.8	0.0	0.0	0.0	0.0
7	2.0	16.8	16.8	8.0	17.6	24.8	24.8	8.0	25.6	32.8	32.8	8.0	33.6	0.0	0.0	0.0	0.0
8	2.0	19.6	19.6	8.0	20.4	27.6	27.6	8.0	28.4	35.6	35.6	8.0	36.4	0.0	0.0	0.0	0.0
9	2.0	22.4	22.4	8.0	23.2	30.4	30.4	8.0	31.2	38.4	38.4	8.0	39.2	0.0	0.0	0.0	0.0
10	2.0	25.2	25.2	8.0	26.0	33.2	33.2	8.0	34.0	41.2	41.2	8.0	42.0	0.0	0.0	0.0	0.0
11	2.0	28.0	28.0	8.0	28.8	36.0	36.0	8.0	36.8	44.0	44.0	8.0	44.8	0.0	0.0	0.0	0.0
12	2.0	30.8	30.8	8.0	31.6	38.8	38.8	8.0	39.6	46.8	46.8	8.0	47.6	0.0	0.0	0.0	0.0
13	2.0	33.6	33.6	8.0	34.4	41.6	41.6	8.0	42.4	49.6	49.6	8.0	50.4	0.0	0.0	0.0	0.0
14	2.0	36.4	36.4	8.0	37.2	44.4	44.4	8.0	45.2	52.4	52.4	8.0	53.2	0.0	0.0	0.0	0.0
15	2.0	39.2	39.2	8.0	40.0	47.2	47.2	8.0	48.0	55.2	55.2	8.0	56.0	0.0	0.0	0.0	0.0
16	2.0	42.0	42.0	8.0	42.8	50.0	50.0	8.0	50.8	58.0	58.0	8.0	58.8	0.0	0.0	0.0	0.0
17	2.0	44.8	44.8	8.0	45.6	52.8	52.8	8.0	53.6	60.8	60.8	8.0	61.6	0.0	0.0	0.0	0.0
18	2.0	47.6	47.6	8.0	48.4	55.6	55.6	8.0	56.4	63.6	63.6	8.0	64.4	0.0	0.0	0.0	0.0
19	2.0	50.4	50.4	8.0	51.2	58.4	58.4	8.0	59.2	66.4	66.4	8.0	67.2	0.0	0.0	0.0	0.0
20	2.0	53.2	53.2	8.0	54.0	61.2	61.2	8.0	62.0	69.2	69.2	8.0	70.0	0.0	0.0	0.0	0.0

Table 4-4: Information Timeliness Example: No response

	Travel time to stop	Bus A				Bus B				Bus C				Lateness		Late. Head.	
Stop #		Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	B	C	B	C
1	2.0	0.0	0.0	8.0	0.8	8.0	8.0	8.0	8.8	16.0	18.0	10.0	19.0	0.0	2.0	0.0	2.0
2	2.0	2.8	2.8	8.0	3.6	10.8	10.8	8.0	11.6	18.8	21.0	10.2	22.0	0.0	2.2	0.0	2.2
3	2.0	5.6	5.6	8.0	6.4	13.6	13.6	8.0	14.4	21.6	24.0	10.4	25.1	0.0	2.4	0.0	2.4
4	2.0	8.4	8.4	8.0	9.2	16.4	16.4	8.0	17.2	24.4	27.1	10.7	28.1	0.0	2.7	0.0	2.7
5	2.0	11.2	11.2	8.0	12.0	19.2	19.2	8.0	20.0	27.2	30.1	10.9	31.2	0.0	2.9	0.0	2.9
6	2.0	14.0	14.0	8.0	14.8	22.0	22.0	8.0	22.8	30.0	33.2	11.2	34.3	0.0	3.2	0.0	3.2
7	2.0	16.8	16.8	8.0	17.6	24.8	24.8	8.0	25.6	32.8	36.3	11.5	37.5	0.0	3.5	0.0	3.5
8	2.0	19.6	19.6	8.0	20.4	27.6	27.6	8.0	28.4	35.6	39.5	11.9	40.7	0.0	3.9	0.0	3.9
9	2.0	22.4	22.4	8.0	23.2	30.4	30.4	8.0	31.2	38.4	42.7	12.3	43.9	0.0	4.3	0.0	4.3
10	2.0	25.2	25.2	8.0	26.0	33.2	33.2	8.0	34.0	41.2	45.9	12.7	47.2	0.0	4.7	0.0	4.7
11	2.0	28.0	28.0	8.0	28.8	36.0	36.0	8.0	36.8	44.0	49.2	13.2	50.5	0.0	5.2	0.0	5.2
12	2.0	30.8	30.8	8.0	31.6	38.8	38.8	8.0	39.6	46.8	52.5	13.7	53.9	0.0	5.7	0.0	5.7
13	2.0	33.6	33.6	8.0	34.4	41.6	41.6	8.0	42.4	49.6	55.9	14.3	57.3	0.0	6.3	0.0	6.3
14	2.0	36.4	36.4	8.0	37.2	44.4	44.4	8.0	45.2	52.4	59.3	14.9	60.8	0.0	6.9	0.0	6.9
15	2.0	39.2	39.2	8.0	40.0	47.2	47.2	8.0	48.0	55.2	62.8	15.6	64.4	0.0	7.6	0.0	7.6
16	2.0	42.0	42.0	8.0	42.8	50.0	50.0	8.0	50.8	58.0	66.4	16.4	68.0	0.0	8.4	0.0	8.4
17	2.0	44.8	44.8	8.0	45.6	52.8	52.8	8.0	53.6	60.8	70.0	17.2	71.7	0.0	9.2	0.0	9.2
18	2.0	47.6	47.6	8.0	48.4	55.6	55.6	8.0	56.4	63.6	73.7	18.1	75.5	0.0	10.1	0.0	10.1
19	2.0	50.4	50.4	8.0	51.2	58.4	58.4	8.0	59.2	66.4	77.5	19.1	79.4	0.0	11.1	0.0	11.1
20	2.0	53.2	53.2	8.0	54.0	61.2	61.2	8.0	62.0	69.2	81.4	20.2	83.5	0.0	12.2	0.0	12.2

Table 4-5: Information Timeliness Example: Immediate response

	Travel time to stop	Bus A				Bus B				Bus C				Lateness		Late. Head.	
Stop #		Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	B	C	B	C
1	2.0	0.0	0.0	8.0	0.8	8.0	8.0	8.0	8.8	16.0	18.0	10.0	19.0	0.0	2.0	0.0	2.0
2	2.0	2.8	2.8	8.0	3.6	10.8	10.8	8.0	11.6	18.8	21.0	10.2	22.0	0.0	2.2	0.0	2.2
3	2.0	5.6	5.6	8.0	6.4	13.6	13.6	8.0	14.4	21.6	24.0	10.4	25.1	0.0	2.4	0.0	2.4
4	2.0	8.4	8.4	8.0	9.2	16.4	16.4	8.0	17.2	24.4	27.1	10.7	28.1	0.0	2.7	0.0	2.7
5	2.0	11.2	11.2	8.0	12.0	19.2	19.2	8.0	**21.0**	27.2	30.1	10.9	31.2	0.0	2.9	0.0	2.9
6	2.0	14.0	14.0	8.0	14.8	22.0	23.0	9.0	23.9	30.0	33.2	10.2	34.2	1.0	3.2	1.0	2.2
7	2.0	16.8	16.8	8.0	17.6	24.8	25.9	9.1	26.8	32.8	36.2	10.3	37.3	1.1	3.4	1.1	2.3
8	2.0	19.6	19.6	8.0	20.4	27.6	28.8	9.2	29.7	35.6	39.3	10.5	40.3	1.2	3.7	1.2	2.5
9	2.0	22.4	22.4	8.0	23.2	30.4	31.7	9.3	32.7	38.4	42.3	10.6	43.4	1.3	3.9	1.3	2.6
10	2.0	25.2	25.2	8.0	26.0	33.2	34.7	9.5	35.6	41.2	45.4	10.7	46.5	1.5	4.2	1.5	2.7
11	2.0	28.0	28.0	8.0	28.8	36.0	37.6	9.6	38.6	44.0	48.5	10.8	49.5	1.6	4.5	1.6	2.8
12	2.0	30.8	30.8	8.0	31.6	38.8	40.6	9.8	41.5	46.8	51.5	11.0	52.6	1.8	4.7	1.8	3.0
13	2.0	33.6	33.6	8.0	34.4	41.6	43.5	9.9	44.5	49.6	54.6	11.1	55.7	1.9	5.0	1.9	3.1
14	2.0	36.4	36.4	8.0	37.2	44.4	46.5	10.1	47.6	52.4	57.7	11.2	58.9	2.1	5.3	2.1	3.2
15	2.0	39.2	39.2	8.0	40.0	47.2	49.6	10.4	50.6	55.2	60.9	11.3	62.0	2.4	5.7	2.4	3.3
16	2.0	42.0	42.0	8.0	42.8	50.0	52.6	10.6	53.7	58.0	64.0	11.4	65.1	2.6	6.0	2.6	3.4
17	2.0	44.8	44.8	8.0	45.6	52.8	55.7	10.9	56.7	60.8	67.1	11.5	68.3	2.9	6.3	2.9	3.5
18	2.0	47.6	47.6	8.0	48.4	55.6	58.7	11.1	59.9	63.6	70.3	11.5	71.4	3.1	6.7	3.1	3.5
19	2.0	50.4	50.4	8.0	51.2	58.4	61.9	11.5	63.0	66.4	73.4	11.6	74.6	3.5	7.0	3.5	3.6
20	2.0	53.2	53.2	8.0	54.0	61.2	65.0	11.8	66.2	69.2	76.6	11.6	77.8	3.8	7.4	3.8	3.6

B. In Table 4-6, bus B is not contacted until stop 9, and because the delay has gotten worse, bus B holds for about ninety seconds. Now buses B and C both have a greater degree of delay, operating at headways of about 12 minutes. If bus C's follower is not held, it will catch up with bus C just before the end of the trip.

Finally, assume that bus C is not considered late until it is five minutes behind schedule, which on Table 4-7 is shown to occur at stop 11. At that time (t=50) bus B is pulling in to stop 16. Any action bus B takes will not affect bus C until stop 16. Not only is 16 very close to the end of the route, but if bus C's follower is not held it will bunch with bus C as they arrive at stop 16. If bus B is held, even for four minutes, the impact will be only on the last quarter of the route.

The total time passengers spend waiting to board a bus in each scenario is a good measure of the effectiveness of the different response times shown. Assuming an even arrival rate, total passenger waiting time for a bus' arrival at a stop can be calculated from the number of people waiting for the bus and the average length of time each person waits. The resulting formula is standard for calculating waiting time:

$$WT = \tfrac{1}{2} \cdot (\text{passengers arriving per minute}) \cdot (\text{headway})^2$$

To calculate the total passenger waiting time for a scenario, we must sum the waiting times for all passengers waiting for each bus at each stop. We will also assume that a bus D starts its trip eight minutes after bus C is scheduled to begin, and stays on schedule in each scenario. Without making this assumption we would have no way to account for those passengers who can board bus C only because it is delayed, but otherwise would

Table 4-6: Information Timeliness Example: Delayed response 1

	Travel	Bus A				Bus B				Bus C				Lateness		Late. Head.	
Stop #	time to stop	Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	B	C	B	C
1	2.0	0.0	0.0	8.0	0.8	8.0	8.0	8.0	8.8	16.0	18.0	10.0	19.0	0.0	2.0	0.0	2.0
2	2.0	2.8	2.8	8.0	3.6	10.8	10.8	8.0	11.6	18.8	21.0	10.2	22.0	0.0	2.2	0.0	2.2
3	2.0	5.6	5.6	8.0	6.4	13.6	13.6	8.0	14.4	21.6	24.0	10.4	25.1	0.0	2.4	0.0	2.4
4	2.0	8.4	8.4	8.0	9.2	16.4	16.4	8.0	17.2	24.4	27.1	10.7	28.1	0.0	2.7	0.0	2.7
5	2.0	11.2	11.2	8.0	12.0	19.2	19.2	8.0	20.0	27.2	30.1	10.9	31.2	0.0	2.9	0.0	2.9
6	2.0	14.0	14.0	8.0	14.8	22.0	22.0	8.0	22.8	30.0	33.2	11.2	34.3	0.0	3.2	0.0	3.2
7	2.0	16.8	16.8	8.0	17.6	24.8	24.8	8.0	25.6	32.8	36.3	11.5	37.5	0.0	3.5	0.0	3.5
8	2.0	19.6	19.6	8.0	20.4	27.6	27.6	8.0	28.4	35.6	39.5	11.9	40.7	0.0	3.9	0.0	3.9
9	2.0	22.4	22.4	8.0	23.2	30.4	30.4	8.0	**32.8**	38.4	42.7	12.3	43.9	0.0	4.3	0.0	4.3
10	2.0	25.2	25.2	8.0	26.0	33.2	34.8	9.6	35.8	41.2	45.9	11.1	47.0	1.6	4.7	1.6	3.1
11	2.0	28.0	28.0	8.0	28.8	36.0	37.8	9.8	38.7	44.0	49.0	11.3	50.2	1.8	5.0	1.8	3.3
12	2.0	30.8	30.8	8.0	31.6	38.8	40.7	9.9	41.7	46.8	52.2	11.4	53.3	1.9	5.4	1.9	3.4
13	2.0	33.6	33.6	8.0	34.4	41.6	43.7	10.1	44.7	49.6	55.3	11.6	56.5	2.1	5.7	2.1	3.6
14	2.0	36.4	36.4	8.0	37.2	44.4	46.7	10.3	47.8	52.4	58.5	11.7	59.6	2.3	6.1	2.3	3.7
15	2.0	39.2	39.2	8.0	40.0	47.2	49.8	10.6	50.8	55.2	61.6	11.8	62.8	2.6	6.4	2.6	3.8
16	2.0	42.0	42.0	8.0	42.8	50.0	52.8	10.8	53.9	58.0	64.8	12.0	66.0	2.8	6.8	2.8	4.0
17	2.0	44.8	44.8	8.0	45.6	52.8	55.9	11.1	57.0	60.8	68.0	12.1	69.2	3.1	7.2	3.1	4.1
18	2.0	47.6	47.6	8.0	48.4	55.6	59.0	11.4	60.2	63.6	71.2	12.2	72.4	3.4	7.6	3.4	4.2
19	2.0	50.4	50.4	8.0	51.2	58.4	62.2	11.8	63.3	66.4	74.4	12.3	75.7	3.8	8.0	3.8	4.3
20	2.0	53.2	53.2	8.0	54.0	61.2	65.3	12.1	66.6	69.2	77.7	12.3	78.9	4.1	8.5	4.1	4.3

Table 4-7: Information Timeliness Example: Delayed response 2

	Travel time to	Bus A				Bus B				Bus C				Lateness		Late. Head.	
Stop #	stop	Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	Sched.	Arr.	Pax	Dep.	B	C	B	C
1	2.0	0.0	0.0	8.0	0.8	8.0	8.0	8.0	8.8	16.0	18.0	10.0	19.0	0.0	2.0	0.0	2.0
2	2.0	2.8	2.8	8.0	3.6	10.8	10.8	8.0	11.6	18.8	21.0	10.2	22.0	0.0	2.2	0.0	2.2
3	2.0	5.6	5.6	8.0	6.4	13.6	13.6	8.0	14.4	21.6	24.0	10.4	25.1	0.0	2.4	0.0	2.4
4	2.0	8.4	8.4	8.0	9.2	16.4	16.4	8.0	17.2	24.4	27.1	10.7	28.1	0.0	2.7	0.0	2.7
5	2.0	11.2	11.2	8.0	12.0	19.2	19.2	8.0	20.0	27.2	30.1	10.9	31.2	0.0	2.9	0.0	2.9
6	2.0	14.0	14.0	8.0	14.8	22.0	22.0	8.0	22.8	30.0	33.2	11.2	34.3	0.0	3.2	0.0	3.2
7	2.0	16.8	16.8	8.0	17.6	24.8	24.8	8.0	25.6	32.8	36.3	11.5	37.5	0.0	3.5	0.0	3.5
8	2.0	19.6	19.6	8.0	20.4	27.6	27.6	8.0	28.4	35.6	39.5	11.9	40.7	0.0	3.9	0.0	3.9
9	2.0	22.4	22.4	8.0	23.2	30.4	30.4	8.0	31.2	38.4	42.7	12.3	43.9	0.0	4.3	0.0	4.3
10	2.0	25.2	25.2	8.0	26.0	33.2	33.2	8.0	34.0	41.2	45.9	12.7	47.2	0.0	4.7	0.0	4.7
11	2.0	28.0	28.0	8.0	28.8	36.0	36.0	8.0	36.8	44.0	49.2	13.2	50.5	0.0	5.2	0.0	5.2
12	2.0	30.8	30.8	8.0	31.6	38.8	38.8	8.0	39.6	46.8	52.5	13.7	53.9	0.0	5.7	0.0	5.7
13	2.0	33.6	33.6	8.0	34.4	41.6	41.6	8.0	42.4	49.6	55.9	14.3	57.3	0.0	6.3	0.0	6.3
14	2.0	36.4	36.4	8.0	37.2	44.4	44.4	8.0	45.2	52.4	59.3	14.9	60.8	0.0	6.9	0.0	6.9
15	2.0	39.2	39.2	8.0	40.0	47.2	47.2	8.0	48.0	55.2	62.8	15.6	64.4	0.0	7.6	0.0	7.6
16	2.0	42.0	42.0	8.0	42.8	50.0	50.0	8.0	**54.9**	58.0	66.4	16.4	68.0	0.0	8.4	0.0	8.4
17	2.0	44.8	44.8	8.0	45.6	52.8	56.9	12.1	58.1	60.8	70.0	13.1	71.3	4.1	9.2	4.1	5.1
18	2.0	47.6	47.6	8.0	48.4	55.6	60.1	12.5	61.4	63.6	73.3	13.2	74.6	4.5	9.7	4.5	5.2
19	2.0	50.4	50.4	8.0	51.2	58.4	63.4	13.0	64.7	66.4	76.6	13.3	77.9	5.0	10.2	5.0	5.3
20	2.0	53.2	53.2	8.0	54.0	61.2	66.7	13.5	68.0	69.2	79.9	13.3	81.3	5.5	10.7	5.5	5.3

wait for bus D. Table 4-8 summarizes the waiting time created by the disruption in passenger-minutes.

Table 4-8: Change in Passenger Waiting Time Given Different Response Times						
		Change in waiting time (passenger-minutes)				
Scenario	See Table:	Bus A	Bus B	Bus C	Bus D	Total
On-time operations	5-3	0	0	0	0	0
Immediate response	5-5	0	294	545	-375	464
Delayed response 1	5-6	0	279	675	-428	526
Delayed response 2	5-7	0	199	989	-496	692
No response	5-4	0	0	1337	-511	826

Even the slowest response results in 134 minutes of savings compared to no response at all, since the few stops at which the response has an impact are the ones where conditions are worse. An immediate response saves 362 passenger-minutes, but a ten minute delay reduces the savings to 300 passenger-minutes. Put another way, the ten minute delay has a cost of 62 passenger-minutes. The longer delay scenario costs 228 passenger-minutes.

This is clearly a simplified example of a real bus route, but the important factors in the effectiveness of holding are all accounted for. With timely information, the route does not deteriorate much, while with poor information, little can be done and the buses bunch. In this one case caused by an initial two minute delay, a response based on timely information can save 228 passenger-minutes compared to a slow one. A more "invasive" technique might have improved the situation, such as expressing the delayed bus, but with timely information it would not have been necessary. When managing a route, early detection of a problem and a fast response time have a significant impact on the response's effectiveness. If it takes an agency too long to respond, some techniques will become less powerful and eventually cease being useful.

Chapter 5: Introducing the Model

In this chapter, we will describe a model created for studying the demands and capacity of a transit agency communications system. Using the decision-making structure of an agency and the volume of problems it experiences, we will model the amount of information that must be carried over each channel during a certain time of day, and the strain it places on those channels. With this model we can measure what recovery techniques can and cannot reasonably be used by the agency, and how this would be affected by different policies and communications channels.

We will first define the assumptions we will be making. We will then learn the methods for representing all these aspects of transit communications. Finally we will formally describe each section of the model.

5.1 Assumptions

There are two critical assumptions underlying this model:

a) *The average of bandwidth from conversations over a long period of time.*

accurately represents the bandwidth of conversations in a specific period of time. One can hypothesize very small systems for which this is not true. For example, imagine a transit agency with one bus and one dispatcher, in which the bus driver must call the dispatcher from a payphone if the bus breaks down, having a conversation that takes six minutes to complete. The bus breaks down every other day, and the driver carries enough change for a five minute phone call. He would be fine on average, as he only needs three minutes of conversation on the average day, but in fact he would be stranded every time his bus broke down.

It is assumed that this effect approaches zero as system size becomes large. If during every rush hour an agency deals with an average of three breakdowns, eight delays, etc. it is assumed that minor fluctuations will not matter. This still does not apply when a major service-impacting event occurs, such as a bus bridge, meaning that such events must be studied separately. Even without such events, there is a slight underestimation of demand on each channel from this assumption.

b) Conversations are consistent in the information given.

This model assumes that when a dispatcher instructs a bus to express, he always gives the same pieces of information, and it always takes roughly the same amount of time. This might not necessarily be the case. One situation might require a great deal of detailed information to be dealt with effectively. As these peculiarities can occur with any given situation, a fixed portion of voice bandwidth is dedicated to conversations about detailed aspects of certain situations.

5.2 Analysis Approach

In this section, we will describe the concepts that are included in the model, and the methods used for modeling them.

5.2.1 Situations, Decisions, and Actions: Structure and Volume

The situations, decisions, and actions that are part of service recovery are based on those studied in chapter 4. To use them in our model we must first customize them for the agency being modeled. Not every agency uses every conceivable recovery technique. CTA, for instance, has no standby buses. For that matter, not every agency faces the same problems. Currently, AMA has no need to provide unplanned bus bridges, as there is no rail to break down and require bus substitution. Further, different agencies have different incidence of situations. Mechanical defects and disruptions may vary according to an agency's vehicle age and composition, its maintenance schedules and operating area characteristics. Even the proportions of decisions and actions in response to these situations may vary from agency to agency. A street layout might prevent expressing down a different route at one agency, or a study of a communications system might show that holding a late bus' leader simply isn't possible.

The volume of problems and the relative proportion of solutions must be customized for each agency and each time of day. Determining the relative proportion of solutions can be difficult, but it is not highly sensitive except between solutions that lead to highly disparate amounts of transmission on particular channels. Short turning and expressing, for example, require about the same amount of transmission: the instruction itself, the location at which to perform the action, and in the case of expressing, the location at which to stop. These volumes and proportions are represented as numbers in select cells in the model, and will be easy to change. The flow of decision-making will be represented by the placement of cells and their reference to each other in certain formulas. Each situation will include rows for each task associated with it and each conversation associated with that task. These cannot be changed automatically, and require personal attention to modify.

5.2.2 Actors and Tasks: Responsibility and Assignment

Every task, whether it is recognizing the existence of a problem, deciding what response is most appropriate, or executing a recovery technique, needs to be done by someone. Most response techniques can only conceivably be performed by one sort of person – it is ultimately the bus driver who expresses or holds a bus, regardless of who makes the decision. Most decisions could reasonably be made by a number of different individuals – a dispatcher or street supervisor could make the decision to short turn a bus – but in most organizations only one or two sorts of individuals actually make these decisions. The model requires an actor to be assigned to any task, and does not differentiate between tasks that must be done by a particular actor and tasks that anyone could do. Actors assigned to tasks are represented both by a value in a cell and the relationship between cells. These cannot be changed automatically, and require personal attention to modify. If different sorts of people perform the same task in a given proportion, splitting responsibility on a certain decision, then this can be represented by dividing the task in to two or more tasks, identical except in their assignment to an actor. Through modification of the volume of each of these choices, one can study the effects of assigning one task to different individuals. Should one want to get around the model's limitation in the ease of assigning a task to different people, it can be done using this technique and changing the proportion of one and then the other task to zero.

5.2.3 Information and Knowledge: Known, Requirements and Transmission

Information and knowledge are reduced to about two dozen different "facts." Each of these facts is tied to four characteristics.

1. It may, or may not, be required for a particular task. For example, one cannot dispatch police to a bus without knowing the bus' location. This is indicated in the model by a table of tasks and facts, with their requirement represented by a true or false value.

2. It may, or may not, always be known by a particular actor. For example, a bus operator will always know the crowding level on his or her bus. This is represented by a similar table to that above, in which actors replace tasks.
3. Each task may, or may not, be transmittable over any given channel. For example, the demand profile of a route cannot be sent using a digital messaging system. This is represented by another true/false table, in which channels take the place of tasks.
4. Each fact consumes a certain amount of bandwidth or strain over any channel it is sent over. For example, it typically takes about four seconds to ask for and learn a bus' location over a radio channel, while it takes about fifteen seconds to ask for and learn the details of a breakdown (see chapter 3.) This is represented by a table of channels and facts, in which the values represent the bandwidth taken by one transmission of a fact.

Any of these can be modified easily and without personal attention.

5.2.4 Strain on Channels: Individual and Total Costs

Each conversation outlined in 5.2.1 details what facts need to be transmitted and what facts actually are transmitted. (The latter is a superset of the former, as policies may require the verification of certain facts.) Also included is the speaker, recipient and channel used. By calculating the frequency with which each conversation occurs, the channel used for each conversation, the facts stated, the strain of each fact, and the strain of starting and stopping the conversation, one can derive the strain being placed on each communications medium. (Note that throughout this chapter, "frequency" will refer to the number of instances of a situation per unit time, and not radio frequency.)

5.3 Model Definition

The pages of this model work together in the following way:

Conversations show what situations occur, what decisions are made, what actions are carried out, and who is behind each task. It addresses the disparity between *Known,* showing what actors know, and *Required,* showing what an actor must know to carry out a task. It presents the facts transmitted for each situation, decision and response, as well as the frequency with which those occur. Those numbers are multiplied by *Strain,* the bandwidth taken by each fact or conversation, to get *Results,* the total load on each communications channel.

5.3.1 Known: What Actors Always Know

This page describes what actors always know. For example a street supervisor does not need to be told the schedules of the buses he oversees, he already has the information. Similarly a bus operator does not need to be told where his bus is, he can see it. This information is captured here.

This page includes:

- One column of the ID number associated with each actor (not used under normal circumstances, but maintained for flexibility of analysis.)
- One column of the name of each actor, one column to the right of the list of actor ID numbers.
- One column for each fact.
- A 1 or a 0 in each cell corresponding to the intersection of one actor and one fact, representing whether the actor knows (1) or does not know (0) the fact.

Table 5-1: A Portion of the "Known" Page				
Actor name	Area bus schedules	Bus availability at garages	Bus schedule	Route demand profile
Bus operator	0	0	1	1
Bus operator off-site	0	0	0	1
Controller	1	1	1	0
Maintenance truck	0	1	0	0
Mobile supervisor	1	1	0	1
Point supervisor	1	1	1	1
Point supervisor on-site	1	1	1	1
All route drivers	0	0	0	1
All area drivers	0	0	0	0
Relieving operator	0	0	0	1

Table 5-1 shows a sample of this page. See appendix A for a complete example.

5.3.2 Required: The Facts Required for Each Action

This page describes what an actor must know to make a particular decision. This does not consider what an actor does or does not already know, or any kind of actor association at all, only whether a fact is necessary to make a decision.

Situations, decisions, and responses are all listed on this page. Decisions and responses are listed once for each situation in which they appear. Because of this, the same response technique can have different information requirements for different situations. As of this writing there are no instances of this in the model.

This page includes:

- A column showing the name of the situation, decision or task. Situations are bold and on a gray background. Decisions are in plain type on a white background and end in a question mark. Responses are in plain type on a white background and do not end with a question mark.

- A column for each fact.
- A 1 or a 0 in each cell corresponding to the intersection of one task and one fact, representing whether the fact is required (1) or not (0) to be aware of the situation, make the decision, or carry out the response.

Table 5-2 shows a sample of this page. See appendix A for a complete example.

Table 5-2: A Portion of the "Required" Page.

Task	Area bus schedules	Bus availability at garages	Bus schedule	Route demand profile
Bus early	0	0	1	0
Are more passengers likely to board?	0	0	0	1
Do nothing	0	0	0	0
Hold bus	0	0	1	0
Bus late (short headway)	0	0	1	0
What response is least disruptive?	0	0	0	1
Do nothing	0	0	0	0
Drop-off only	0	0	1	1
Express down a different street	0	0	1	1
Express to a later point	0	0	1	1
Follower picks up passengers	0	0	0	0
Hold leader prefol / hold leader	0	0	0	0
Short turn	0	0	1	1

5.3.3 Conversations: The Conversations that Stem from Each Situation

This page is the heart of the model. It outlines what conversations take place in the course of dealing with every situation, how often they take place, what is said, who says it, and over what channel.

On this page, each row corresponds to a part of a task. The rows generally go down in chronological order and not all rows have the same meaning. Some of the rows represent information that is required to make a decision or initiate a response; some rows represent the knowledge of a certain actor; some rows represent the set of knowledge that is both necessary and absent for a particular decision; some rows represent the information being sent over a particular communication channel. Let's talk about the contents that are common to each row before discussing how rows differ and relate to each other.

The columns, from left to right, are:

1. "Situation." The name of the situation
2. "Frequency." The number of times a situation, or a specific step, arises per unit time.
3. "Step" and "Step detail." These two columns define the type of row. "Step" can be a description of knowledge or communication. It can also be a decision or response as listed in *Required,* in which case "Step detail" may define the row further.
4. "Channel." What channel a conversation is taking place on, if applicable. Represented with a number.
5. "#." The ID number of the actor speaking or acting in this row.
6. "Actor." The name of the actor speaking or acting in this row.
7. "Total." The total of the fact columns. This is only used for certain rows, as a checksum (see below.)
8. Facts, Instructions, and Conversation overhead: These cells are 1 or 0, depending on whether the item is active for the present row. What "active" means, and how this is derived, depends entirely on the meaning of the row, as defined in "Step"

and "Step detail." Instructions represent whether instructions are given, and conversation overhead represents the overhead cost of each conversation.

Table 5-3 shows the different kind of rows, as defined with "Step" and "Step detail."

Table 5-3: Meanings of Rows in "Conversations" Page

Step	Step detail	Row description
Awareness	-	Shows the actor who becomes aware of a problem, and the facts necessary to do so. The facts are copied from *Required.*
Reports to	-	Shows the person conveying facts, the channel over which it is conveyed, and the facts that are conveyed. Data is entered manually (not derived automatically.)
Known by	-	Shows the facts that a particular actor has. These are derived by what they have learned so far OR'ed with what the actor knows in *Known.*
Decision / Response	Needed	Shows what facts are needed to make a decision or implement a response. This data is copied from *Required.*
Decision / Response	Needed and unknown	Shows what facts an actor slated to make a decision or implement a response needs but does not yet have. Derived logically from the "Needed" row and the "Known by" row if one is present for the given actor, or the *Known* sheet if no "Known by" row is present.
Decision / Response	Instructs	The facts and other communications overhead relayed by a given actor over a given radio channel. This applies to instructing an actor to take an action. This is done manually and compared by hand to "Needed and unknown."*
Decision / Response	Announces	The facts and other communications overhead relayed by a given actor over a given radio channel. This applies to announcing that a certain action has been taken, as when a dispatcher informs street supervisors that he has expressed a bus. This is entered manually.
Decision / Response	Announces & Instructs	The facts and other communications overhead relayed by a given actor over a given radio channel. This applies to instructing that an action be taken and simultaneously notifying any who need to know over the same channel. This is entered manually and compared by hand to "Needed and unknown."*

* If agencies transmitted exactly the facts that the model deemed necessary, these rows could by copied directly from "Needed and unknown," with only the "Instructions" and "Conversation overhead" filled in manually. However, agency practices often dictate that information is sent which is not deemed necessary by the model. Deriving this by hand yields more accurate results.

Table 5-4 shows a sample of this table, the rows associated with a Crush Load in a model of the Chicago Transit Authority. For a full example of this page, see appendix A. Walking through the rows of this table will help explain the process of this page. Note that some columns have been skipped over due to space constraints, including "Situation type," "Frequency," and a number of facts. The column "Row" has been added to aide this description.

- Row 1, Awareness, shows the facts necessary to recognize a crush load situation. The facts are copied from *Required.* None of the shown facts are active, although the fact "Existence of problem" is active but not shown. Actor is "bus operator" because he is the only one who is initially aware of the situation.
- Row 2, Reports to C/PCC, shows the initial message send to the C/PCC. This is sent on channel 3, which is the Digital Data channel. This data is inputted directly, based on knowledge of CTA's digital system. Note that Conversation overhead is true. This value must be true once for every conversation.
- Row 3, Reports to supervision, shows the message being relayed from the C/PCC to street supervision. This information is, again, entered manually. Note that both the channel and actor are different from row 2, as this is a controller speaking over the supervisor radio channel.
- Row 4, Known by supervision, shows what supervision now knows. This is derived from ORing row 3 with what street supervisors already know, as stated in *Known.*
- Row 5, What response is least disruptive? – Needed, is copied from the corresponding row in *Required.*

Table 5-4: Selection of "Conversations" Related to Crush Load. Some columns have been skipped over due to space limitations. "Row" has been added to aide the accompanying text.

Row	Step	Step detail	Channel	Actor #	Actor	Total	Area bus schedule	Bus availability at garages	Bus sched.	Bus location	Instructions	Conversation overhead
1	Awareness			1	Bus operator		0	0	0	0	0	0
2	Reports to C/PCC		3	1	Bus operator		0	0	0	1	0	1
3	Reports to supervision		1	3	Controller		0	0	0	1	0	1
4	Known by supervision						1	1	1	1	0	0
5	What response is least disruptive?	Needed					0	0	1	0	0	0
6	What response is least disruptive?	Needed and unknown		6	Point supervisor	0	0	0	0	0	0	0
7	Do nothing						0	0	0	0	0	0
8	Drop-off only	Needed					0	0	1	0	0	0
9	Drop-off only	Needed and unknown		1	Bus operator	0	0	0	0	0	0	0
10	Drop-off only	Instructs	4	6	Point supervisor		0	0	0	1	1	1
11	Drop-off only	Announces	1	6	Point supervisor		0	0	0	1	1	1
12	Hold prefol / hold leader	Needed					0	0	0	1	0	0
13	Hold prefol / hold leader	Needed and unknown		1	Bus operator	0	0	0	0	0	0	0
14	Hold prefol / hold leader	Instructs	4	6	Point supervisor		0	0	0	1	1	1
15	Hold prefol / hold leader	Announces	1	6	Point supervisor		0	0	0	1	1	1

- Row 6, What response is least disruptive? – Needed and unknown, is derived by ANDing row 5 with the opposite (NOT) of row 4. In this case, the total is 0, showing us that there is nothing that supervisors need to know that they do not already know. This verifies that they can make the decision without any additional communications.
- Row 7, Do nothing, is one of the three possible responses supervisors might make. Because it involves taking no action, the columns in this row have no significance.
- Row 8, Drop-off only – Needed, is the information needed to implement the second of three possible responses. This is copied from *Required.*
- Row 9, Drop-off only – Needed and unknown, shows what facts the bus driver would require to operate drop-off only service, but does not have. It is derived by ANDing row 8 with the opposite (NOT) of the Bus operator entry in *Known.* The total figure excludes the instruction, which includes the points between which the operator is to operate in drop-off only service.
- Row 10, Drop-off only – Instructs, shows what facts the point supervisor gives to the bus operator. This includes the conversation overhead, and of course Instructions. Communications method 4 represents face-to-face communication.
- Rows 12 through 15 are functionally the same as rows 8 through 11, but for a different recovery technique. These are all the rows associated with Crush load.

5.3.4 Strain: The Bandwidth Taken by Each Transmission of a Fact

This page describes the bandwidth used by transmitting a fact over each given means of communication, as well as whether such a transmission is possible. "Instructions" and "Conversation overhead" also appear here.

This page contains four sections.

1. *Transmittable:* Whether each fact is transmittable on each channel.
2. *Asking for:* The strain of asking for each fact on each channel.
3. *Relaying:* The strain of reporting each fact on each channel.
4. *Total:* The total strain of asking for and reporting each fact on each channel.

The general format for each of these is as follows:

- One column shows the ID number associated with each channel.
- One column shows the name of each channel.
- A column for each fact.
- A column for "Instructions," and a column for "Conversation overhead."
- For *Transmittable,* each cell contains a TRUE or FALSE value, representing whether the corresponding can be conveyed on the corresponding channel. "Instructions" and "Conversation overhead" are marked as TRUE for all channels.
- For *Asking for* and *Relaying*, the cell contains the bandwidth taken by asking for or relaying the fact. The definition of bandwidth can vary by channel, but it is typically the number of seconds taken to say something over the radio (see chapter 3.)

- "Instructions" is zero in *Asking for*, as instructions are not asked for. Their only value is in *Relaying*. For "Conversation overhead," only the sum of *Asking for* and *Relaying* matter, so they can be distributed however one wishes.
- For *Total*, cells calculate the sum of the corresponding cells in *Asking for* and *Relaying*.

Table 5-5 shows a sample of *Transmittable*. See appendix A for a complete example of this page.

5.3.5 Results: The Total Strain on Each Channel

This page shows the total strain on each communications method. This is derived from *Conversations* and *Strain*. For each channel, the rows of *Conversations* which use that channel have their facts multiplied by the row's Frequency and their corresponding strain. The sum of this is the total channel use.

Table 5-5: A Portion of the "Transmittable" Chart

Channel ID	Channel	Area bus schedules	Bus availability at garages	Bus schedule	Route demand profile
1	Sup radio	FALSE	TRUE	TRUE	TRUE
2	Bus chan	FALSE	TRUE	TRUE	TRUE
3	Digital data	FALSE	FALSE	FALSE	FALSE
4	Face to face	TRUE	TRUE	TRUE	TRUE

Chapter 6: Application of the Communications Model to the Chicago Transit Authority

In the previous chapter, we developed and described a communications model. In this chapter, we will apply that model to the Chicago Transit Authority's bus communications system. We will first describe the sources of the necessary data for our model. We will then walk through a portion of model creation, to show explicitly how this is done. We will discuss the results and implications of an analysis of CTA's current system of communication, followed by the same for a hypothetical communications system with wireless PDAs.

6.1 Data Sources

In this section, we will describe the sources of data necessary for the model. There are three principle sources used: recordings of CTA radio traffic, to measure the length of time taken to ask questions, state answers, and give instructions over the air; queries to CTA's central events database to determine the volume of events; and personal observation in CTA's Communications / Power Control Center, with accompanying interviews, to determine the order and nature of decisions and responses particular to CTA.

6.1.1 Communication Bandwidth Usage: Voice Recordings

The author obtained a one-week sample of voice recordings of CTA's radio channels. This tape contained recordings of every voice channel, including the two bus supervisor radio channels and three digitally managed channels shared by buses, as well as a number of channels for rail lines, security, and power control. These recordings were stored on a Dictaphone Prolog tape, playable on Dictaphone Prolog and Guardian equipment.

The author listened to all supervisor and bus channels from 8:30-9AM, 11-11:30AM and 3-3:30PM on Monday, September 10 2001. These samples were chosen because they represented three distinct and consistent levels of activity, as indicated by the number of disruptions logged in the control center's database (see next section.) A sample of conversation follows with minor details altered to preserve employee privacy. When numbers are given they are printed once as numbers for readability, followed by the phonetics in italics. The sample, at 3:07PM on September 10, 2001, concerns bus 5876 which has been sending false silent alarms. The control center handles this as a minor mechanical defect, allowing the bus to continue in service until there is an opportunity to take it off the street without disruption. In this exchange the dispatcher asks street supervisor K321 to address the problem by trading buses, and the supervisor asks for clarification on what bus it is.

Control: K321 *(K three twenty-one)*: earlier bus number 5876 *(fifty-eight seventy-six)* was giving out several false alarms. When the operator reaches your location sir will you trade that bus off?

K321: 10-4 (*Ten-four)*, gimmie the run again.

Control: No run number is available, sir. The bus number is 5876 *(fifty-eight seventy-six)*.

K321: 5876, 10-4 *(Fifty-eight seventy-six, ten-four.)*

The author broke down these conversations into pieces representing the facts being conveyed or parts of conversational overhead and used an audio editing program to measure the length of time these pieces took to say. Also marked was whether it would be accounted for in the model – a supervisor announcing that buses were jumping reliefs would be accounted for in the model, but a supervisor repeating himself because static interfered would not. Time spent silent was also noted. The following Table 6-1 shows such a representation of the conversations above:

Table 6-1: Breakdown of a Conversation			
Start Time and duration	Speaker	Words	Purpose
3:07:39 (2 seconds)	Control	K321: …	Overhead (starts conversation)
3:07:41 (6 seconds)	Control	earlier bus number 5876 was giving out several false alarms….	States existence of problem
3:07:48 (5 seconds)	Control	When the operator reaches your location sir will you trade that bus off?	Gives instructions
3:07:53 (1 second)	K321	10-4…	Overhead (confirming message)
3:07:54 (2 seconds)	K321	gimmie the run again.	Outside model (requesting repetition)
3:07:56 (4 seconds)	Control	No run is available, sir. The bus number is 5876.	Outside model (repetition)
3:08:00 (2 seconds)	K321	5876, 10-4.	Outside model (repetition)

From this data, we are able to determine the average amount of time it takes to ask for or relay some information, or to offer instructions or describe a problem. For instance, it takes six seconds to state the nature of a problem in the sample above, while the average value is 6.5. Some pieces of information were not discussed over the air, such as a bus' lead headway which is not generally known. In these cases, likely hypothetical times were determined through comparison with existing data and a limited amount of experimentation. Statements given by bus operators at CTA are consistently slower than their dispatcher or supervisor counterparts, as they spend so much less time on the radio. To represent this, the strain of information on the digitally managed bus channels is the strain of the information on supervisor channels multiplied by a fixed value (1.5) which provided results consistent with samples.

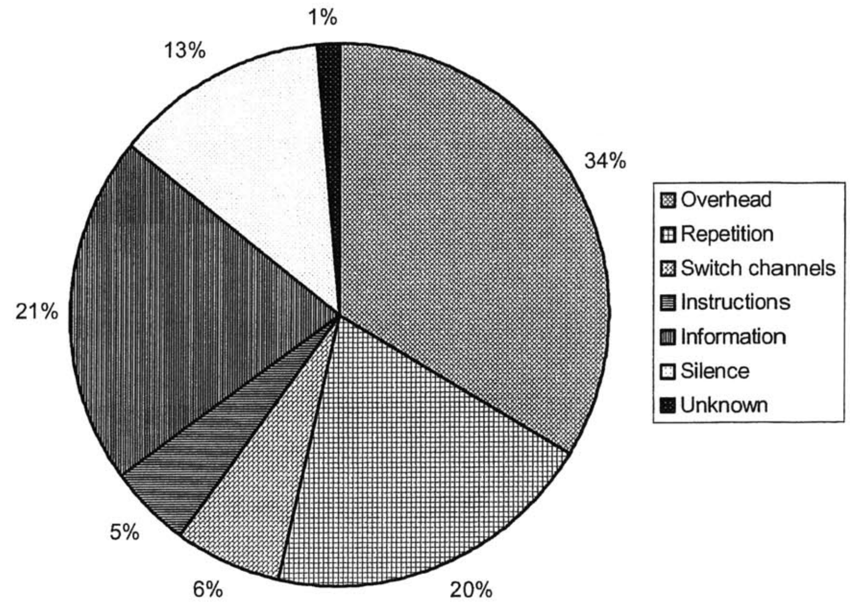
We can also determine how much conversation takes place that the model cannot account for. We assume that this is a constant value – that no matter what is under discussion, a fixed number of statements will need to be repeated, and a fixed number of issues too complicated to be described by the previous chapter's methodology will arise. (This makes sense in the context of this study, as complicated issues generally cannot be moved to data messaging and stay on a voice channel.) We can then consider this portion of capacity to be unavailable.

As CTA has a "primary" and an "alternate" channel for supervisors, some time on the primary channel is used by supervisors instructing each other to switch to the alternate channel for a conversation. This extra time is averaged in to the time taken to start and end a conversation.

Figure 6-1 shows how the time on the primary radio channel was used during the 3 to 3:30pm sample.

- "Overhead" refers to conversational overhead, such as asking the dispatcher for permission to speak, acknowledging a message, etc.
- "Repetition" refers to the need to repeat anything due to interference or inattention.
- "Switch channels" refers to a request to switch to the alternate radio channel, including the overhead for that conversation.

Figure 6-1: Use of CTA Supervisory Radio, 3-3:30pm



- "Unknown" refers to any words the author could not decipher, and the rest are self-explanatory.

Of note is that although this is an off-peak time period, the channel is silent just 13% of the time, indicating that it is approaching capacity. Overhead, repetition and channel management occupy 60% of the total time, or 69% of the time that someone is speaking. Also noteworthy is that despite a location being announced for almost every disruption, it takes only 14% of the time spent giving information or 3% of the total. Knowledge of city geography allows dispatchers and supervisors to indicate a location very quickly.

From the demand placed on the channel used in the afternoon, the reader may expect that demand would exceed supply during the peak, which is correct. The need to communicate occurs at random intervals, and a supervisor will only relay some messages if he can do so in a timely fashion and if there is enough unused capacity available to warrant using it. Therefore there are occasional short pauses. But on the 8:30 to 9AM sample there were no pauses of thirty seconds or more. The ramifications of this will be discussed below.

See chapter 3 and appendix B for more information on these communication methods and an analysis of CTA's voice channels, respectively.

6.1.2 Event Volume: The BECS Database

Everything that passes through the bus side of CTA's Communications / Power Control Center (C/PCC) is logged in CTA's Bus Emergency Communications System database. This database can be used to learn the amount of time it takes for the C/PCC to respond to a disruption, which bus controllers had a role in the disruption, even the amount of service delay caused by different disruptions. For this thesis, the author measured the number of disruptions that typically occur during different times of day. This information was obtained by averaging the number of disruptions of each type starting in each hour on all Wednesdays for one year. (Analysis on total disruption volume showed no significant variation between weekdays, with the exception of an increase in disruptions on Friday night. Wednesdays were chosen at random.)

Some events treated separately in the model are considered together in the BECS database. For instance, the model differentiates between three kinds of mechanical defects: those that do not keep the bus out of service, those that keep the bus out of service but do not immobilize it, and those that immobilize it. The BECS database does not make these distinctions. When numbers needed to be broken down, inference based on interviews and personal experience was used.

Some events are listed under the generic heading of talk request or priority talk request. This occurs when a driver chooses to push the "Request to talk" or the "Priority request to talk" button instead of sending a digital message, usually because of unfamiliarity with the mobile data terminal's menus. To rectify this, talk request time was distributed among bus delay, mechanical problem, emergency, accident, missed relief, blockage, and congestion according to the existing proportion of those conditions. Priority talk requests were distributed between emergency and accident according to the existing proportion of those conditions.

The event "bus early" does not pass through the control center at all. Because these disruptions did not result in any communications in any scenario, the number of early buses has no impact on the results of the model, so a reasonable guess was made.

Figure 6-2 shows the volume of events throughout the day, averaged by hour, and Table 6-2 shows the resulting amount of disruptions to be used in the model. Not only are disruptions at CTA subject to peaking, but different disruptions peak at different times. In the morning, equipment defects peak from 7 to 8 as buses pull out and enter service. Delays peak in rush hour from 8 to 9, and emergencies peak from 9 to 10. Also of note is that equipment defects only vary by about five per hour between 6am and 5pm, while delays peak far more dramatically in the same period, ranging from about 5 per hour to 22.

Figure 6-2: Disruption Volumes by Hour Throughout Day

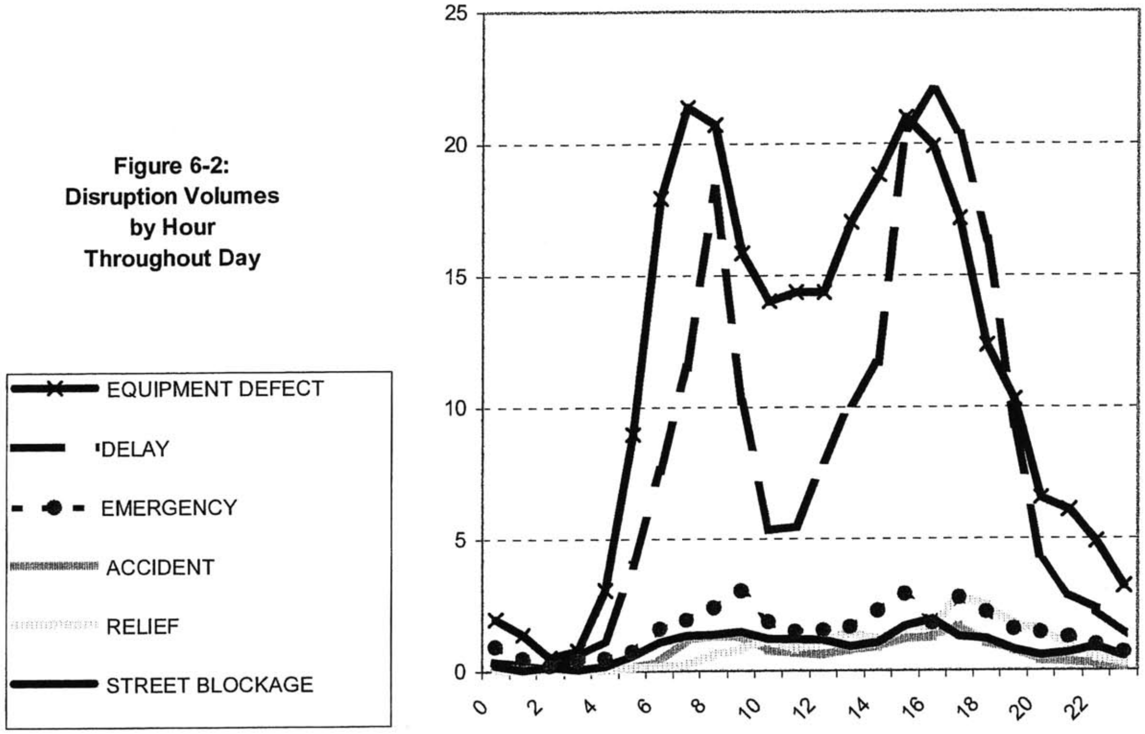


Table 6-2: Model Input: Number of Events in Time Periods		
	8-9am	3-4pm
Bus early	10	8
Bus late (short headway)	12	8
Bus late (long headway)	6	4
Crush load	1	2
Mechanical problem (minor)	6	5
Mechanical problem (serious)	2	2
Mechanical problem (major)	12	10
Emergency / Security	2	2
Accident	2	1
Operator misses relief	0	4
Blockage	2	2
Bus standing / service gap	26	21
Unfilled run	22	17
Unplanned bus bridge	0	0
Route-wide congestion	2	1
Late pull-out	4	5

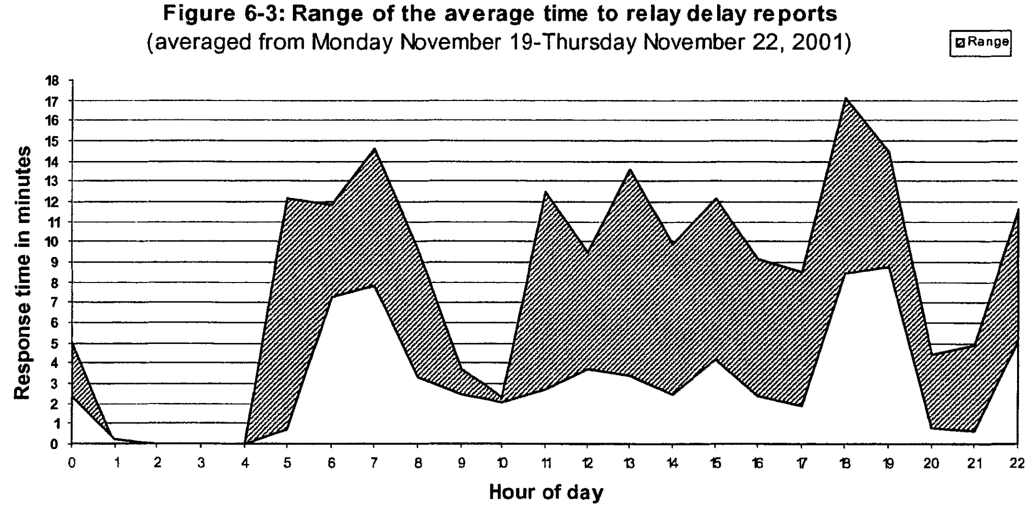
One can also use the BECS database in conjunction with an understanding of control center procedure to determine an upper and lower bounds of the length of time between the control center receiving a message and acting on it, although this is only possible for certain messages. To do so it helps to understand basic roles with the control center: garage controllers are responsible for communicating with a certain number of buses, and the "C1" controller is responsible for communications with the supervisors. The controllers use computers that put incoming digital messages in an event queue. So when information travels from a bus to supervisors through the control center it actually goes through two different people. For example, when a bus sends a delay report of less than thirty minutes to the control center, the control center's role is to relay it to street supervisors, who can order a response to the disruption if appropriate. Within the control center, the following sequence of events takes place:

1. The message appears in the event queue of a garage controller
2. The garage controller sends the message from his computer to the event queue of the C1 controller
3. The C1 controller announces the delay over the air
4. The C1 controller "closes" the message, removing it from his queue, or sends it back to the garage controller, who closes it

The control center database logs the time at which the message was received, the times it is sent from one controller to another, and the time it is closed. The C1 controller announces the message over the air at some point between receiving it and sending or closing it, presenting an upper and lower bound. Figure 6-3 shows the average bounds on the time it takes the control center to relay these delay messages by time of day, from information gathered from four days. (A four day period was chosen because the necessary information is only stored in the database for a short time. This measurement may include a small number of duplicate delay reports that were never announced over the air at all, however the results are corroborated by extensive personal observation.)

The actual level of time is likely to be closer to the upper bound, as C1 controllers typically close a delay message as soon as they have announced it to make more room in their queue and ensure that they do not announce it again. It is notable that while the garage controller's performance exhibits peaking, C1's does not. One explanation for this would be that C1 does not consider delay messages "urgent," and so focuses heavily on other disruptions, which peak less.

Figure 6-3: Range of the average time to relay delay reports
(averaged from Monday November 19-Thursday November 22, 2001)



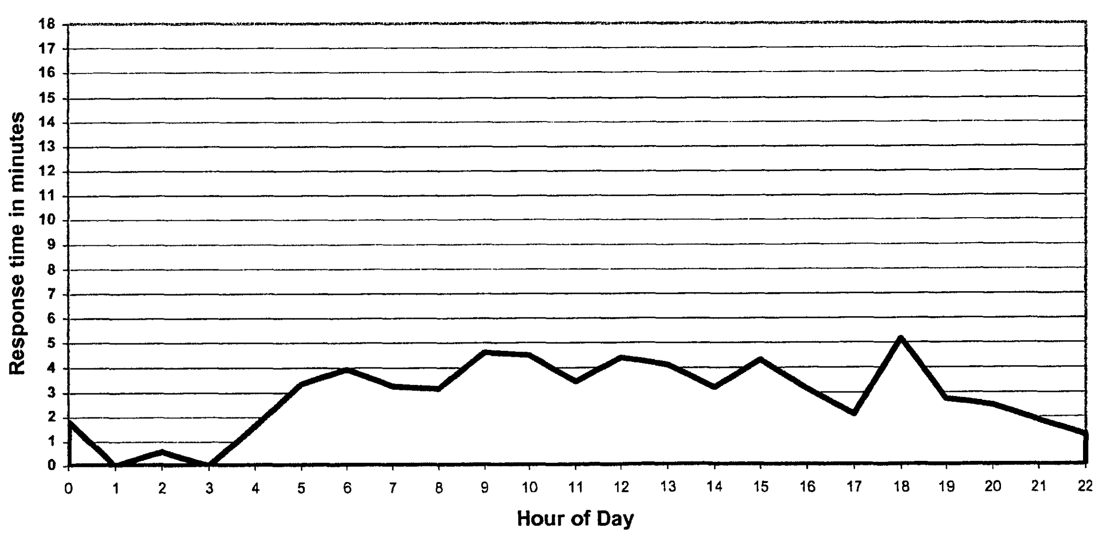
Delays are also among the most time-sensitive reports, due to the tendency of a late bus to become even later in the absence of any intervention (see section 4.4.) Because these reports are for buses that are already at least 10 minutes late and take on the order of ten minutes to get to supervisors, this information is only rarely useful for supervisors. The implications of this will be discussed later in the chapter.

Delay reports are some of the slowest to be relayed, because dealing with accidents and mechanical breakdowns takes priority within the C/PCC. A higher priority event is a mechanical defect. When a bus sends a digital message reporting an equipment defect, the following events occur:

1. The message appears in the event queue of a garage controller
2. The garage controller usually makes voice contact with the bus for more information
3. The garage controller sends the message, including the new information he has gathered and his recommendation for the next action, from his computer to the event queue of the C1 controller
4. The C1 controller assigns the equipment defect to a particular street supervisor, mobile supervisor or repair truck, as appropriate
5. The C1 controller leaves the message in his queue until the party assigned to fix the problem reports back with a resolution
6. The C1 controller then "closes" the message, removing it from his queue

Because no digital event takes place after C1 assigns the problem to someone in the field, one cannot learn an upper bound on the time taken to relay this message. The lower bound is displayed in Figure 6-4.

Figure 6-4: Lower Bound of Average Time to Relay Equipment Defect Reports (averaged from Mon. Nov. 19-Thurs. Nov. 22, 2001)



Contacting the bus operator for more information typically takes two to three minutes, so on average a garage controller is starting work on the disruption within one or two minutes of receiving a message. The lack of peaking in this delay is noteworthy in light of the peaking in disruption volumes shown in Figure 6-2, and is evidence of the higher priority placed on this form of disruption. Personal observation indicates that the taken to relay the message is typically 1-2 minutes above the lower bound shown, and occasionally on the order of five minutes during a peak period. As the options for responding to an equipment defect do not diminish over time, this is an entirely effective timeframe for relaying messages, although less than ideal for responding to an associated service gap.

See appendix B for more information about and from the BECS database.

6.1.3 Communications and Decision-Making Procedures: Observations, Interviews and Inference

The roles and responsibilities of different CTA personnel in response to different disruptions, including the communications each initiates, the decisions each makes and the actions each takes, is of central importance to the model. The decision flow framework established in chapter 4 and the checks built into the model itself help dictate what is possible, but that must still be narrowed down to what actually happens or would happen in an alternate scenario.

A model of existing CTA procedures was based on personal observations of CTA supervisors and dispatchers, in-depth interviews with 6 dispatchers, and interviews with a number of CTA employees[1]. A model of alternative CTA procedures, supported by new

[1] Darryl Lampkins, George Neal, Tom Pleuger, and Daniel Shurz.

communications technology, was based on the goals of the project as described by Tom Pleuger, the existing procedures, and the framework established in chapter 4. While a complete model of procedures is not shown, samples of the chain of command and sequence of events resulting from certain disruptions will appear later in this chapter.

6.2 Model Walk-Through

This section will walk through the remaining steps in implementing the model introduced in the previous chapter. This includes filling in the tables representing the steps CTA takes when dealing with a disruption, noting any inconsistencies in model results, and adjusting the tables to ensure reasonable and accurate results.

6.2.1 Creating and Understanding Conversation Tables

Here we will map the agency's process for dealing with disruptions onto the existing structure of what communications this process will generate. This is done using a combination of the framework in chapter 4 and knowledge of operations. Let us start with a simple example to see how this is done. Figure 6-5 shows graphically how CTA deals with an accident, and Table 6-3 shows the model's representation of it. To conserve space in the model, only relevant pieces of information are

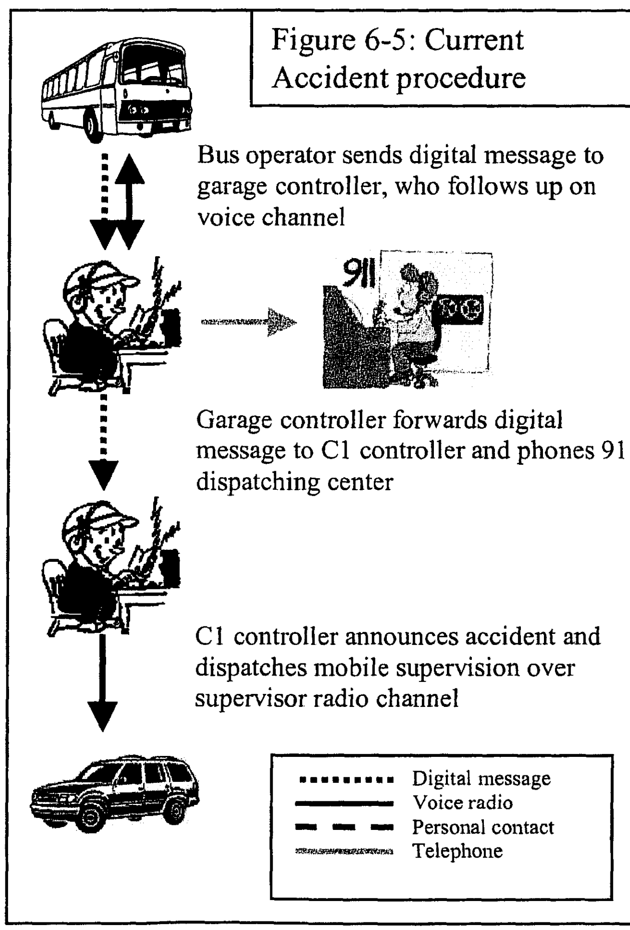


Figure 6-5: Current Accident procedure

Table 6-3: Modeling How CTA Responds to Accidents					
#	Step	Step detail	Chan.	Actor	Information
1	Awareness			Bus operator	Existence of problem
2	Reports to C/PCC		Digital	Bus operator	Problem, location
3	C/PCC asks for detail		Bus radio	Controller	Detail of problem
4	Known by controller			Controller	Problem, location, detail
5	Are medics needed?	Needed			Problem, detail
6	Are medics needed?	Needed & unknown			
7	Dispatch mobile super.	Needed			Problem, location, detail
8	Dispatch mobile super.	Needed & unknown			
9	Dispatch mobile super.	Announces & Instructs	Super. radio	Controller	Instruction, Problem, location, detail
10	Dispatch police	Instructs	Phone	Controller	Problem, location, detail
11	Dispatch police, medics	Instructs	Phone	Controller	Problem, location, detail

shown. Some data, like the number of times a step occurs, is omitted.

The following description shows what each row represents.

1. What a bus operator must know to be aware of the event. As this is an accident, he simply needs to know that the accident has occurred.
2. The bus operator reports the accident to the control center using digital communication. The digital message includes the nature of the incident and the bus' location.

3. The control center calls the bus operator on the digitally managed voice channel and asks the bus operator for details on the situation. This row does not represent the entire conversation, because every accident has an accompanying mechanical defect, which also requires this step. See below for an example of this conversation.
4. What the controller knows. In this case, it is no more than what he has been told.

5. What a controller needs to know to decide whether medics are necessary: the existence and details of the event.
6. What a controller needs to know, but does not know to decide whether medics are necessary. This row is empty, as it should be: he knows everything he needs to. This row serves as a confirmation that the procedure described makes sense.
7. What the controller must know in order to dispatch mobile supervision to the accident: the existence of the event, the location and details. Details are necessary to prioritize the event properly.
8. What the controller must know, but does not know, to dispatch mobile supervision. As in row 6, this serves as a check.
9. The controller announces the accident over the supervisor radio channel, and in the same conversation, dispatches mobile supervision to the scene. While this is not the same controller, the distinction is not relevant for this model. As with row 3, this row does not represent the entire conversation. See below for an example of this conversation.
10. The controller telephones the 911 center to dispatch police.
11. The controller telephones the 911 center to dispatch police and medics.

The number of times each row is counted in the model is equal to the number of times the step it represents occurs during the given time period. All rows but 10 and 11 are counted once for each accident; the number of times rows 10 and 11 are counted must sum to the number of accidents. If, for example, CTA contacted the police over its supervisory radio channel but had to telephone a 911 center for medics, this distinction would be necessary. As this is not the case, they could be combined, but are left separate for consistency with the framework introduced in chapter 4.

While the model does not represent or create actual conversations with real information, representing the values in rows 3 and 5 in this fashion can be illustrative of the relationship. Following are two entirely fictional and idealized conversations to show what is being represented. Statements in bold are the only ones with corresponding values in the accident table. All other rows are represented in the tables of other disruptions that necessarily accompany an accident. The first, corresponding to row 3, is the conversation between the controller and the bus operator.

1. *Dispatcher*: Run 612, pick up your handset please.
2. *Driver*: Run 612.
3. *Dispatcher*: Run 612 what is your bus number and badge number?
4. *Driver*: Bus number 1642, badge 38925.
5. *Dispatcher*: And what is your location and direction?
6. *Driver*: I'm at the corner of Addison and Pulaski, facing east.
7. ***Dispatcher*: Run 612 can you describe what happened?**
8. ***Driver*: I was pulling in to the stop when I felt a bump behind me. I heard it to. I looked in my mirror and a car had hit me. But it drove off.**
9. ***Dispatcher*: Are there any injuries?**
10. ***Driver*: No, no injuries.**
11. *Dispatcher*: Have you looked at the damage?
12. *Driver*: Yeah, the corner of the bus is kind of banged up. The light is broken. Some paint's scratched. But still runs OK.
13. *Dispatcher*: OK, I'm passing this on supervision, you stay there until you're clear.
14. *Driver*: 10-4.

Statements 1 through 6 and 14 show the overhead of the conversation. They occur whenever a dispatcher speaks with a bus operator. While all the information gathered is transmitted with the original digital signal, dispatchers still ask this information to verify that it is correct. Statements 7 through 10 represent the detail of the problem. Statements 11 and 12 represent the detail of the equipment defect. 13 represents the instructions given. In this case, every statement not represented in the accident table is represented in the equipment defect table.

The following represents the conversation indicated in row 9. In this case, the dispatcher continually reports a number of distinct pieces of information. To facilitate explanation his statement is broken into a number of rows, even though they represents one uninterrupted statement. Abbreviations are explained in line with text.

1. *Dispatcher*: Attention K12.
2. Run 612, 1642 on the bus, stands
3. at 74th and Polaski
4. **after a 10-73 [collision of CTA vehicle and another vehicle]**
5. **with an auto. No injuries have been reported, vehicle reported to have left the scene.**
6. bus is not disabled and has been taken out of service.
7. 10-51[Go to location and assist as appropriate], please, 10-51...
8. Also your attention K181 and K187, your attention to the Addison route.
9. *K12:* K12, 10-4.

Rows 1 and 8 represent the overhead of the conversation. Rows 2 and 4 represent the statement of one problem, a mechanical defect. Those rows, the location in row 3 and the instruction in row 7 are all represented by values in the mechanical defects table. Rows 4 and 5 represent the existence and detail of an accident, statements represented in the accident table. Row 8 represents the statement of the a gap in service, represented in the bus standing / service gap portion of the table.

6.2.2 Adjusting Goals to Results

Everything is in place for us to calculate the demand on channels, and all that remains is determining the supply. Tables 6-4 and 6-5 show the supply provided by two open mic supervisory channels and three digitally managed bus radio channels, respectively. It should be noted that while bus operators typically speak more slowly than supervisors, they lose less time to overhead because less repetition is necessary.

Table 6-4: Supply on Supervisory Channels Available for Conversations Represented in Model

(seconds)	Primary channel	Secondary channel
Seconds in an hour	3600	3600
Seconds lost to repetition and conversation outside of model:	-1116	-1116
Seconds lost to inefficiencies from using two channels*:		-1332
Remaining capacity	2484	1152
Total remaining capacity:	**3636**	
*Time spent switching channels and establishing new conversation on alternate channel		

Table 6-5: Supply on Digitally Managed Bus Channels Available for Conversations Represented in Model

(seconds)	Channel 1	Channel 2	Channel 3
Seconds in an hour	3600	3600	3600
Seconds lost to repetition and conversation outside of model:	-789	-789	-789
Remaining capacity	2811	2811	2811
Total remaining capacity:	**8433**		

We can now divide the seconds of demand predicted by the model by the seconds of supply, showing our preliminary results in Table 6-6:

Table 6-6: Use of Radio Channels, CTA Today (Preliminary)				
Time	Supervisor channels		Bus channels	
	Observed	Predicted	Observed	Predicted
8-9AM	about 100%	116%	About 75%*	79%
3-4PM	87%	101%	--	62%
* A rough estimate based on personal observation.				

This is clearly not an accurate picture of channel use. Even disregarding the observed values, CTA cannot use more than 100% of its supervisor channels' supply. If demand on the radio outweighs supply, the radio becomes a constraint, and some communication about less vital disruptions is dropped. When individuals compete for airtime, people who know they have a less pressing need will tend to forgo it, and if they do not, C1 will ask them to wait while more urgent matters are discussed.

The disruptions which do not absolutely have to be dealt with are:

- Bus late (short headway)
- Bus late (long headway)
- Crush loads
- Service gaps (spreading the terminal)

Let us try leaving announcements that buses are late on the supervisor radio channel, as they are standard operating procedure, but removing any supervisor discussion of service responses, removing discussions in response to crush loads, and removing about half of the conversations resulting from service gaps. We must do this consistently for all time periods. While it is true that supervisors could change their behavior during certain times of day, in general they behave consistently throughout the day. 50% of a weekday's delays occur in just 20% of the time (8-9 AM and 3-7PM.) Over the course of a career, a supervisor will deal with a majority of delays when communications are very busy. It is unlikely that he will try to use more communication bandwidth to try more ambitious techniques for the minority of delays that occur during the off-peak, a time when he may perceive delays as less disruptive.

The number of disruptions occurring during different time periods, as shown in Table 6-2, does not change. All that changes is how they are dealt with, and the results are shown in Table 6-7:

Table 6-7: Use of Radio Channels, CTA Today (Adjusted)				
Time	Supervisor channels		Bus channels	
	Observed	Predicted	Observed	Predicted
8-9AM	about 100%	97%	About 75%*	68%
3-4PM	87%	89%	--	62%
* A rough estimate based on personal observation.				

Observing these results without comparing them to any observed data, we find that they appear very realistic. It does not show channels being used more than is possible, but it does show use very close to maximum capacity in the peak period. As we had to reduce communications to get here, this makes sense: we have established above that this channel is a constraint at peak, so we would expect use of it to be at about 100%. Now, by comparing these results to observed data, we see that we are producing accurate results.

To test these results further, we can compare the makeup of the demand between the conversations depicted by the model and the conversations observed. Figure 6-6 compares the predicted uses of supervisory radio for both time periods and the observed

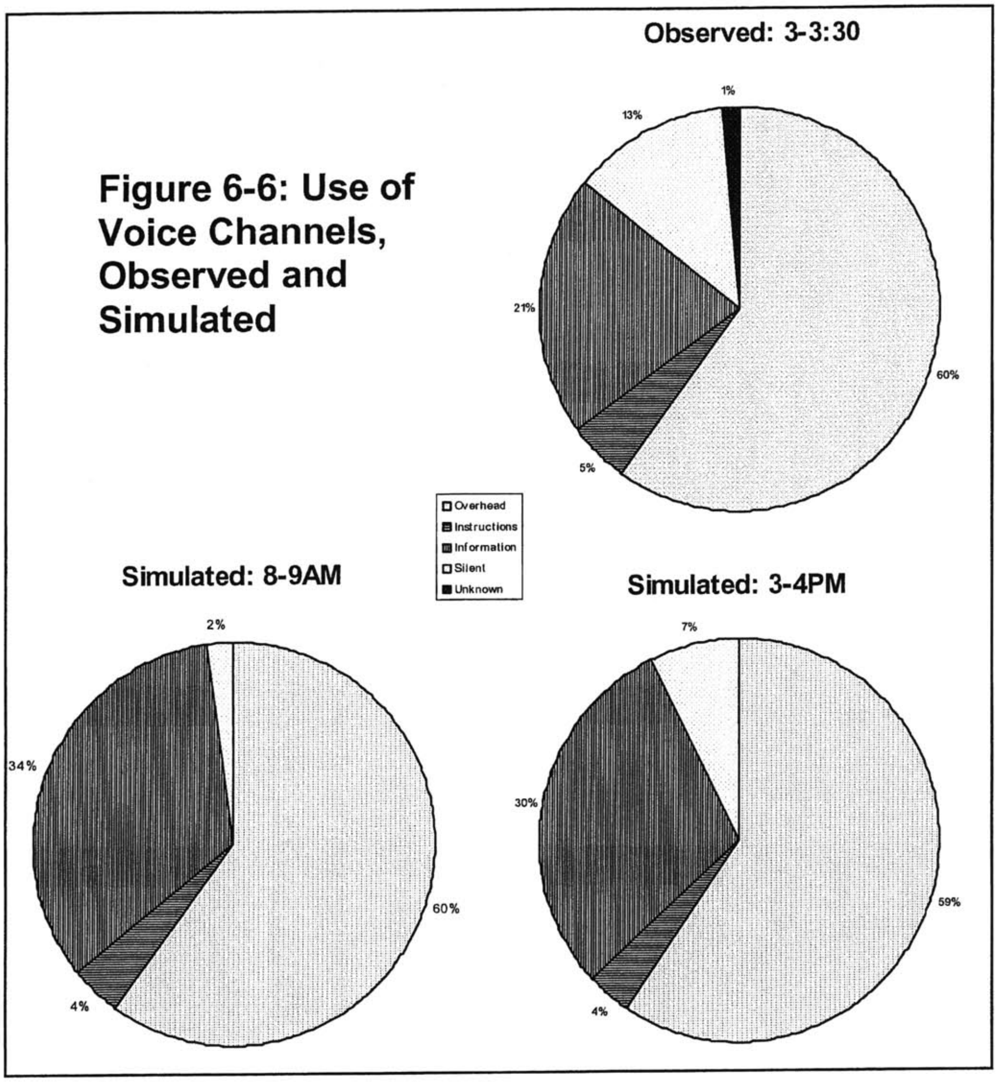


Figure 6-6: Use of Voice Channels, Observed and Simulated

use for one. The model combines multiple kinds of overhead, so for ease of comparison overhead appears as one value in the observed chart as well.

The demand being placed on the supervisory radio, both in total and grouped by type of use, is consistent with observed data. One must note that even if the numbers in our simulated and observed afternoons happened to match exactly, it would not mean that the demand placed on the channel will always be 89% of its capacity between 3 and 4 on weekdays. The number and kinds of disruptions fluctuates randomly, and so does demand for communication. Adding three more accidents and one unfilled run to our 3:00 scenario pushes the predicted demand to 100%. But we can say that on an average day, about all of the supervisory radio is used at peak, about nine tenths is used off peak, and discussion related to most non-critical disruptions (delays, crowding, service gaps, unfilled runs) is being omitted.

We can now evaluate what that means.

6.3 Implications for CTA: Available Service Restoration Options

We have built a model around how CTA's procedures are designed to handle disruptions, and adjusted it according to the limitations that communications puts on those procedures. We can now draw some conclusions concerning how this affects service.

First, let us look at how CTA handles accidents and breakdowns. Figure 6-7, reprinted below, shows how CTA responds to an accident. (See section 6.2.1 for more detail on this procedure.) When revising the model's communication demand figures to bring them within supply

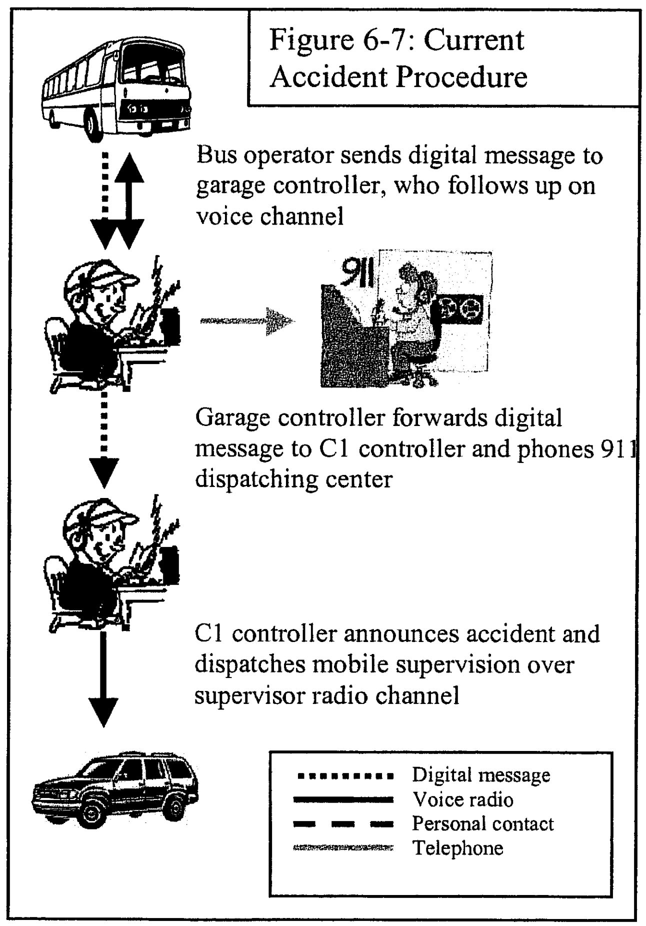
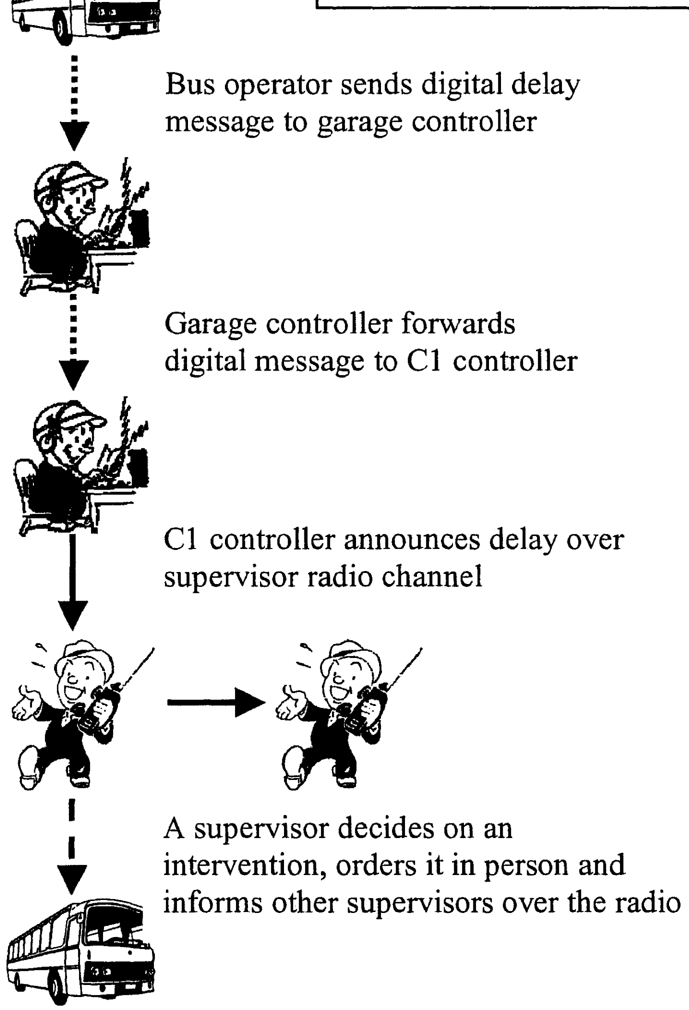


Figure 6-7: Current Accident Procedure

there were no changes made that concerned accidents (although some changes did concern service gaps, which accidents do cause.) By returning to Figure 4-9, which the model representation was partly based on, we can see that all responses to an accident are accounted for by CTA procedure. The bus operator gives supervision all the information they need to make the best possible decision. In this case, the only decision the dispatcher makes is a simple one, whether to request medical services when sending police to the scene. Accidents are a high priority and can go over the air right away.

Responses to breakdowns, while similar in structure to accidents, may not reach the supervisors as quickly in peak periods because there is so much use of the supervisor channels. In practice, mobile supervisors are often very busy in the peak and have several assignments waiting, so they usually cannot proceed to the disabled bus as soon as it is announced. Communications

Figure 6-8: Implied Delay Procedure



is not a constraint in this case.

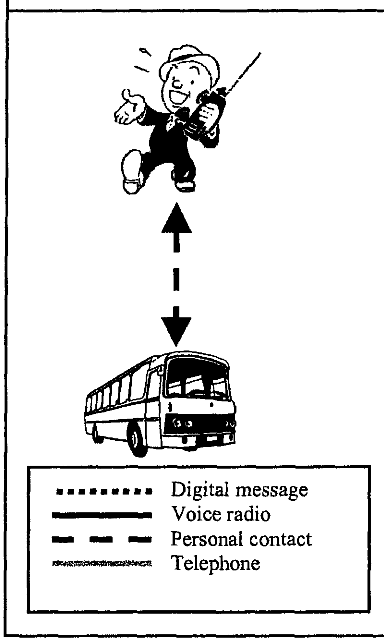
Delays are more complicated. CTA reporting procedures imply that the organization is to respond to delays in the manner shown in Figure 6-8 and described in section 6.1.2. A supervisor must decide on and implement a recovery technique, if any. Based on this procedure and the information and resources necessary to choose and implement a response to a delay on a short headway route, as shown in Figure 5-2, we can say that the following techniques shown in Table 6-8 should be available for supervisors to respond to these delays:

Table 6-8: Implied CTA recovery techniques to a delay on a short headway route

Technique	Possible?	Constraints	Cost
Express down a different street	*Yes*	Not until bus reaches supervisor	somewhat unpredictable
Express to a later point	*Yes*	Not until bus reaches supervisor	somewhat unpredictable
Drop-off only	*Yes*	Not until bus reaches supervisor	somewhat unpredictable
Short turn	*Yes*	Not until bus reaches supervisor	somewhat unpredictable
Hold leader	*Yes*	Not until bus' leader reaches supervisor, questionable effectiveness	Predictable
Do nothing	*Yes*	None	Predictable

If the capacity on supervisor radio channels was not a constraint, every recovery technique would be possible, but every technique has constraints and holding a leader is particularly difficult. As observed in chapter 4, a bus whose leader is held continues to become increasingly delayed until it reaches the point where the leader had been held. We also observed that this technique is most effective if implemented as soon as the bus is at all late. So while a supervisor could technically hold a leader, it is rarely possible to do effectively. For the rest, costs are somewhat unpredictable because the cost to some passengers depends on the time they will now have to wait for the following bus. Using CTA's reporting system, that bus could be up to nine minutes late and the supervisor would not know yet. (He would know the follower's location if the buses are bunched, and if not he may or may not be able to find out from another supervisor on the route, depending on supervisor placement.) This does not impact the effectiveness of returning the bus to schedule, but would aide in deciding between some responses. For example, when deciding between expressing and operating as drop-off only, expressing can return a bus to schedule faster but forces some passengers to alight and wait for the next bus. The length of time they would wait can make the difference between the two techniques.

Figure 6-9: Actual delay procedure



We have established in 6.1.2 that the delay information that goes through the control center is not actually useful to supervisors most of the time. In theory, multiple supervisors along a route could still share information about late buses to form a picture of a route, but as demonstrated in section 6.2.2 there is not enough radio supply to support this level of detailed exchange during the period when most delays take place. The resulting procedure for intervening in delays is to do so through direct contact between supervisors and buses, as shown in Figure 6-9, resulting in the available techniques shown in Table 6-9:

Table 6-9: Implied CTA Recovery Techniques to a Delay (Short Headway Route)			
Technique	Possible?	Constraints	Cost
Express down a different street	*Yes*	Not until bus reaches supervisor	Very unpredictable
Express to a later point	*Yes*	Not until bus reaches supervisor	Very unpredictable
Drop-off only	*Yes*	Not until bus reaches supervisor	Very unpredictable
Short turn	*Yes*	Not until bus reaches supervisor	Extremely unpredictable
Hold leader	*No*	N/A	N/A
Do nothing	*Yes*	None	Predictable

Holding a leader is no longer possible because a supervisor only has the opportunity to do so before he is aware of the problem. Costs have become more unpredictable for two reasons. One is that a bus' follower could be an number of minutes late without the supervisor knowing. The follower could be further behind schedule than the bus in question, in which case it could be fortunate that the bus in question is late, whether or not it was deliberately held. More fundamentally, a supervisor does not know whether other restoration actions are occurring on the route, and runs the risk of making a decision that would compound the inconvenience to certain customers. If a supervisor expresses a bus on the assumption that its follower is not far behind, and another supervisor has short-turned that follower to bring him back on schedule, passengers will be inconvenienced more than either of them could expect.

Under such circumstances, a supervisor's best decision is often to do nothing. If a bus is so late it will miss its next trip, or the bus is bunched with a follower, a supervisor may be reasonably sure than an intervention will do more good than harm. In the former case the cost of inaction is greater, and in the latter case the cost of intervention is both smaller and more predictable. Otherwise, doing nothing is the only course where the costs are known. On average, another technique might have a net positive effect, but doing nothing has the most appealing worst-case scenario.

Major delays and bunched buses can still be addressed, but this strategy is ineffective against small delays. Unfortunately as noted in chapter 4 a minor delay has a tendency to become worse, until it reaches the end of its route or becomes a major delay or a bunched bus. A delay cannot be addressed until it becomes a significant problem. The limits on communication between buses and supervisors have a negative impact on service.

6.4 Predicting the Impact of PDAs on CTA

A proposal exists within CTA to give wireless PDAs to street supervisors. These handheld computers would allow supervisors to communicate with the control center, buses and each other using digital messaging. They would allow supervisors to track the location of a bus or all the buses along a selected route. In addition, software would detect when a bus is behind schedule and inform supervisors automatically. In an email from CTA, Tom Pleuger estimated the cost at $80,000 for hardware plus 4 man-months of development totaling $152,640 (Tom Pleuger, 2002.) This does not include time spent solving existing procedural problems that would prevent the PDAs from being useful. For example, the digital information from buses is sometimes incorrect, such when a bus operator does not log in properly or when a bus is digitally "assigned" to a different garage than the one out of which it actually works. These inaccuracies cause problems for existing operations unrelated to PDAs, and this analysis assumes that they will be addressed.

To model this we must first determine the changes in CTA procedure. Procedures for accidents and breakdowns would not change a great deal, while handling of delays would change significantly.

To divide work efficiently among a group of people, a person needs to keep track of who is doing what and who is the least busy. The only question is whether dividing work between supervisors is easier or more difficult with digital messaging. Voice radio is ideally suited to this task: a dispatcher can give out assignments rapidly, discussion can move back and forth easily to determine who is free, and anyone can say whatever information is relevant to assigning someone to a problem. Digital messaging is weak in these areas. This is not to say that digital dispatching is not done, and done well. But when it works it is because computers at both ends work to optimize the dispatching tasks: keeping track of people's assignments for the dispatcher, prioritizing assignments for each person in the field, letting the people in the field mark a job as "complete" automatically and removing it from the assignment list, and generally taking over a lot of the dispatcher's work load. The PDA proposal for CTA does not have these qualities, so we will assume that dispatching will continue to be done by voice, which is easier. The one exception is the report from supervisors that a job is finished: it would be more convenient for a dispatcher to receive these digitally so he could choose his free moments to deal with them. But most dispatching would still go over the radio.

Delay management, by contrast, is perfectly suited to be handled digitally. The control center's only role in delays is relaying information, which in this case can be done more quickly without it. Delay reports would no longer be necessary over the supervisor radio. Supervisors would be aware of the position of all buses on their routes, and be able to see delays as they begin to develop. If supervisors use the PDAs to send digital messages to each other, then announcements about responses to delays – and, significantly, rescheduling the street – would no longer be necessary. Such messages are of a more predictable and routine nature than those associated with dispatching, and so can be easy to send digitally. Figure 6-10 shows this new relationship, and Table 6-10 shows the recovery techniques that can be used as a result:

Figure 6-10: Delay Procedure with PDAs

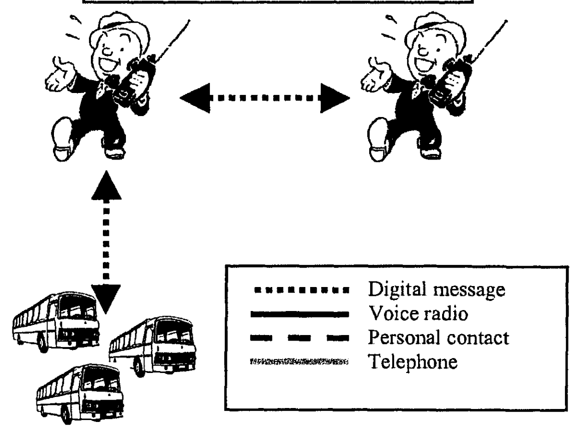


Table 6-10: CTA Recovery Techniques to a Delay (Short Headway Route) with PDAs			
Technique	Possible?	Constraints	Cost
Express down a different street	*Yes*	Not until bus reaches supervisor	Predictable
Express to a later point	*Yes*	Not until bus reaches supervisor	Predictable
Drop-off only	*Yes*	None	Predictable
Short turn	*Yes*	Not until bus reaches supervisor	Relatively predictable
Hold leader	*Yes*	None	Predictable
Do nothing	*Yes*	None	Predictable

. Some assumptions underlie this list:

- A supervisor will only express or short turn a bus he can see, because:
  - He can make a better decision knowing the load of the bus
  - He may prefer to give the instruction personally to ensure that it is understood (especially when expressing down a different street)

    - He will want to be on the scene to personally make sure that passengers can board freely

- A short turn is less predictable than other techniques because it usually occurs shortly before the bus reaches its terminal. If the bus that will be its follower hasn't started its trip yet, there is no way to know with certainty what the bus' following headway will be.

Given that holding a bus is an effective technique for recovering from minor delays, and given the tendency of late buses to become later, we can say that this puts the CTA in a substantially better position in two ways:

1. Supervisors can *prevent many minor delays from becoming significant delays.*
2. Supervisors can *make more informed choices in responding to major delays.*

Another important change is that PDAs allow supervisors to reschedule a street to compensate for a missing run, even if they are not stationed at the terminal. This is important because few of CTA's terminals have a supervisor, making respacing very difficult on those routes.

The majority of delays would be dealt with by holding, but other techniques will be used as well. It is not clear whether supervisors will feel comfortable using techniques like expressing without announcing their intentions over the radio. They may feel comfortable informing the route's other supervisors digitally, or they may state the intervention over the air to give others a chance to object. Table 6-11 summarized all the results relating to supervisory radio channels, including two for PDA deployment. "With announcements" assumes that expressing, short turning, and street rescheduling involve announcements over the radio. "Without announcements" does not.

Table 6-11: Supervisor Channel Summary		
	8-9AM	3-4PM
Observed	about 100%	87%
Initial prediction	116%	101%
Adjusted prediction	97%	89%
PDA with announcements	78%	71%
PDA without announcements	52%	50%

Two thirds of the difference between the two PDA results is time spend rescheduling the street. CTA experiences many service gaps, because so many disruptions create one: unfilled runs, accidents, equipment defects, disturbances, and missing reliefs (if jumping reliefs is not possible) all create service gaps. The degree of automation the PDAs provide in addressing service gaps has a major influence on the use of the supervisory radio. Currently, the absence of supervisors from most terminals prevents a lot of street rescheduling, and the crowded state of supervisory radio means it is not consistently announced. So the estimate of the amount of discussion this takes was based on a fairly small sample of data. The difference this makes on the supervisor radio may therefore be exaggerated, but there is no denying that this is an important function for supervisors to make effective use of their PDAs. If the devices show schedule adherence data that data must change to reflect the schedule that is actually being used when a street is rescheduled.

In general PDAs provide a significant reduction in supervisor radio traffic. This will serve to make the job of the dispatcher assigned to that channel easier. It will allow for faster dispatching, particularly in the peak, and would also allow for more discussion which could lead to better dispatching decisions. It is not clear whether either of these will result in an improvement in service. Dispatching assignments a few minutes faster in the peak may not have an impact because supervisors almost always have a job to finish before they can go on to another assignment. Nor is there evidence to indicate that dispatchers need more time discussing assignments to do so effectively. However it can only be good to have more free time on the channel, and on days when there are a particularly large number of delays and accidents (such as a rainstorm) this prevents responses to each from interfering with responses to the other. Delays peak more severely than any other form of disruption, so it is good to move them to digital communication, which scales well.

There are other benefits to the PDA deployment. Mobile supervisors will be able to find buses more quickly using first hand location information. This is particularly useful when dealing with silent alarms. Supervisors may gain a new understanding of how their routes work by being able to see all of it in detail. Similarly their judgment may improve as they see the full picture of their intervention's results, and as they watch the results of interventions of those they work with. Digital record-keeping of the bus' locations and supervisor messages can be used for employee evaluation and statistical information. The most important benefit, however, will be the creation of direct communication between supervisors and buses, allowing for better recovery from delays and other disruptions.

Most of these benefits are very difficult to quantify, but one that we are in a position to estimate is the value of using holding to prevent minor delays from becoming major. It would be problematic to estimate these benefits by comparison with other agencies' experiences. The change could be significantly greater than that experienced by Tri-Met or Denver RTA, given that CTA would go from no communication between buses and supervisors to digital tracking, and given that CTA would have one supervisor looking at information for every 20 buses, as compared to one dispatcher for every 200 buses in Denver (Mary D. Stearns, 1999.) However an approximation can be made based on the examination of the importance of information's timeliness in section 4.4 and some information from CTA. According to the BECS database, bus operators sent 15,277 "ten minute delay" reports in one year, and that on average they report the load at time of delay as 56% of capacity. (September 1, 2000-2001, excepting major storms. See appendix B.) A conservative assumption would be that 10% of these delays could be detected with PDAs and addressed with holding. An assumption that this would reduce the delay by about one half would be consistent with the demonstration in section 4.4, in which immediate holding reduced passenger wait time by 44%. An assumption that bus operators perceive 60 passengers as a bus' capacity would indicate that on average there are 34 passengers on board each delayed bus. Multiplying these numbers shows a savings in one year of 257,880 passenger minutes or almost a year of passenger waiting time. A 1999 study Resource Systems Group did for the Chicago Department of Transportation estimated waiting time at ten cents a minute, which would amount to a $25,788 annual net benefit (Stacey Falzarano et. al., 2000.) This is a very conservative estimate, and doubling the number of actionable delays from 10 to 20% would double the resulting benefits while remaining a reasonable assumption. If this were the only benefit of the PDAs they would take 5-10 years for the investment to start producing net benefit. Because holding as a means of reducing passenger delay is just one of many responses and goal they support, this analysis bodes very well.

New communications systems can suggest different distributions of responsibility, but in this case PDAs would make the existing division of responsibility substantially easier.

By providing location information and communications to buses in the field, supervisors are significantly better equipped to manage the spacing of a route and are poised to save hundreds of thousands of passenger-minutes annually just by applying one kind of technique to one kind of problem. The control center, aware of all the situations that require mobile supervision or repair trucks, remain in the best position to coordinate the workloads of numerous response units.

Assuming that existing procedural issues are addressed, the use of wireless PDAs would have a significant impact on CTA's most pressing communication problems with no discernable negative impact and would provide a good return on investment.

Chapter 7: Summary and Conclusions

This thesis has studied the impact of the relationship between information, communication and responsibility on bus service management. In this chapter, the findings of this work will be reviewed. Conclusions will be drawn and finally future work will be suggested.

7.1 Findings

Disruptions have a predictable set of potential responses. Information is necessary to choose and implement a response.

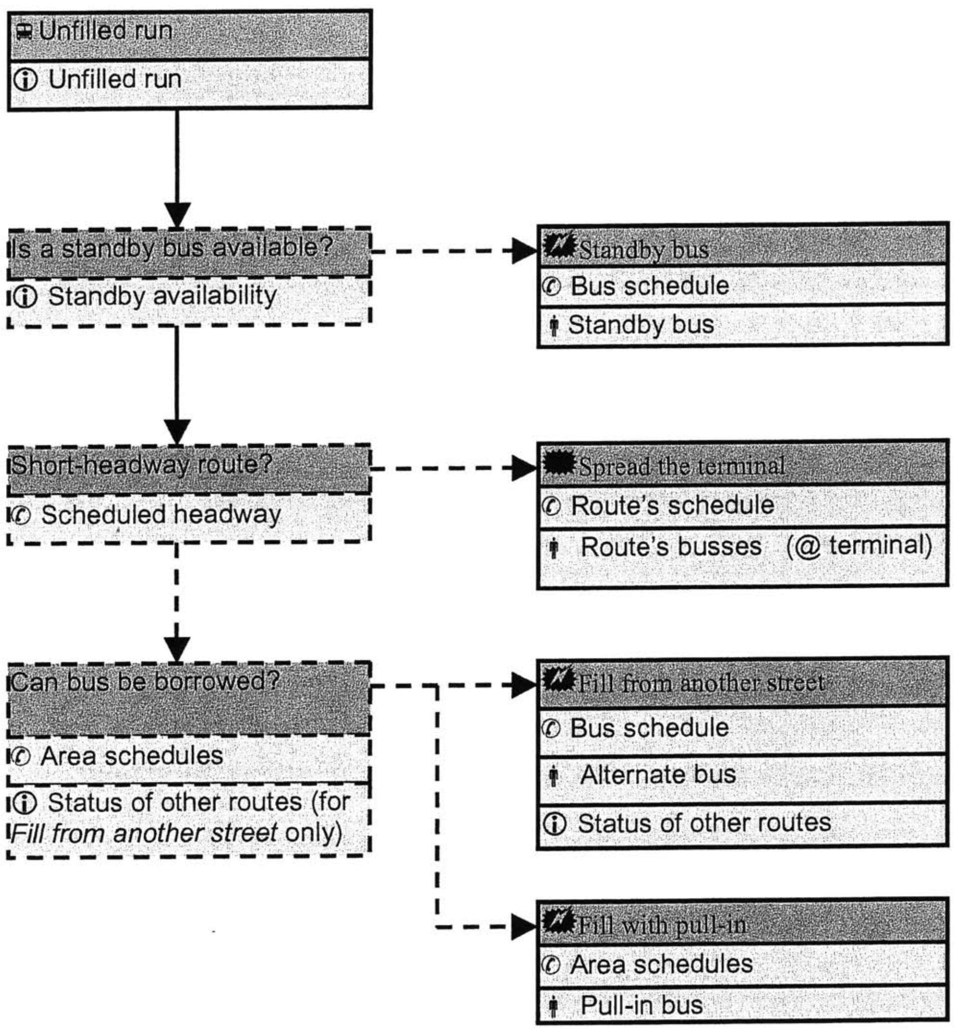
Figure 7-1, reprinted from chapter 4 below, shows the decisions and responses that step from an unfilled run. There may be variations from one transit agency to another. Some may not have standby buses, for example. Generally, however, for a given disruption there is a set of responses that can be used, a set of information necessary to implement each response, and a set of information necessary to choose the best response.

Disruptions, though random, occur with a predictable frequency throughout the day. At CTA, delays and equipment defects experience significant peaking, while other disruptions peak only slightly.

Figure 7-2, reprinted from chapter 6 below, shows the frequency of various disruptions throughout the weekday at CTA. It would not be reasonable to assume that the same pattern applies at other agencies. It would be reasonable to assume that other agencies do have patterns. Knowledge of these patterns can help an agency plan to deal with them more effectively.

Figure 7-1: Unfilled run

See also: Bus standing / service gap



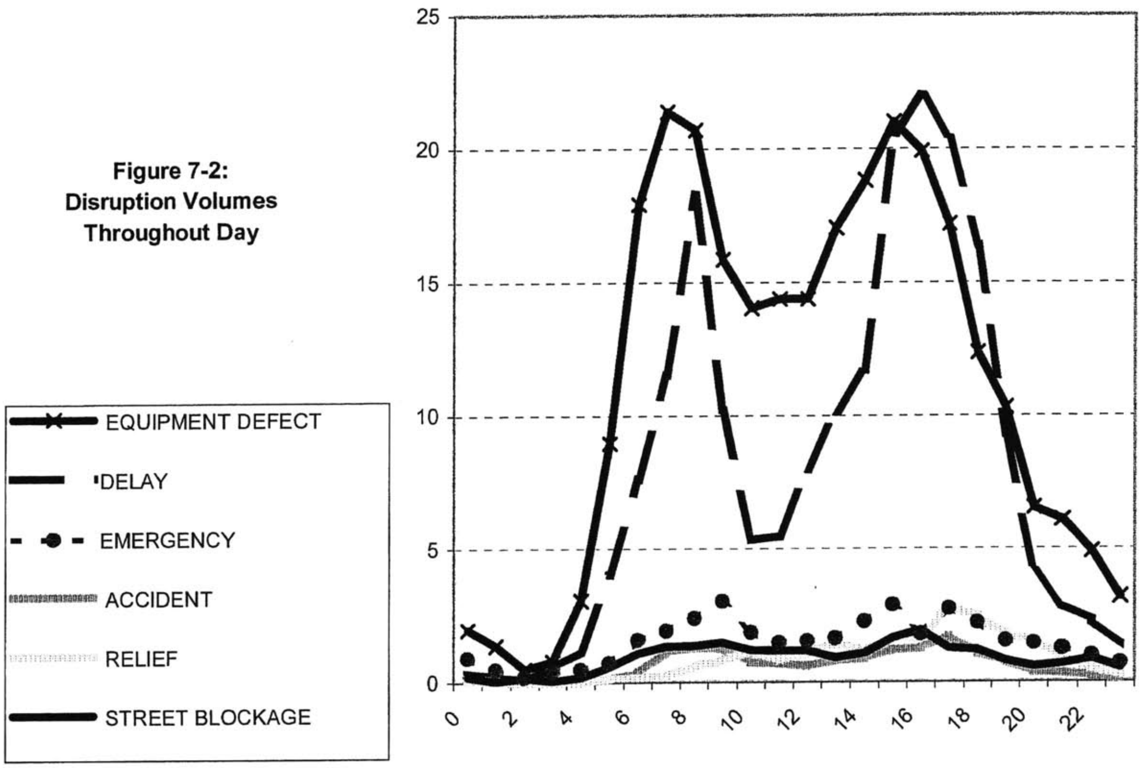


Figure 7-2: Disruption Volumes Throughout Day

Communication channels at CTA do not have enough capacity to meet demand, creating a constraint restricting available restoration actions, especially to delays.

Table 7-1, reprinted below from chapter 6, summarizes the findings of the load on CTA's supervisory radio channels. The limited capacity of the supervisory channels prevents information about "non critical" disruptions, such as delays, from going out in a timely manner. It also prevents supervisors from discussing these events unless they become so serious that they could be considered critical. Table 7-2 shows the difficulty a supervisor faces in responding to a delay. In general, a supervisor at CTA can only feel confident intervening in a very serious delay, because the cost of his intervention is unpredictable to him.

Table 7-1: Supervisor Channel use Summary		
	8-9AM	3-4PM
Observed	about 100%	87%
Initial prediction	116%	101%
Adjusted prediction	97%	89%
PDA with announcements	78%	71%
PDA without announcements	52%	50%

Table 7-2: Implied CTA Recovery Techniques to a Delay (Short Headway Route)			
Technique	Possible?	Constraints	Cost
Express down a different street	*Yes*	Not until bus reaches supervisor	Very unpredictable
Express to a later point	*Yes*	Not until bus reaches supervisor	Very unpredictable
Drop-off only	*Yes*	Not until bus reaches supervisor	Very unpredictable
Short turn	*Yes*	Not until bus reaches supervisor	Extremely unpredictable
Hold leader	*No*	N/A	N/A
Do nothing	*Yes*	None	Predictable

PDAs would allow CTA to make better restoration decisions and address schedule issues more effectively.

Table 7-1 above shows the difference in radio traffic that PDAs would make, which can help in dispatching in response to incidents. Table 7-3 below shows the improvement in a supervisor's ability to choose and implement a response to a delay that PDAs would provide. Supervisors would have more options and would be able to make better decisions, resulting in more effective service restoration.

Table 7-3: CTA Recovery Techniques to a Delay (Short Headway Route) with PDAs			
Technique	Possible?	Constraints	Cost
Express down a different street	*Yes*	Not until bus reaches supervisor	Predictable
Express to a later point	*Yes*	Not until bus reaches supervisor	Predictable
Drop-off only	*Yes*	None	Predictable
Short turn	*Yes*	Not until bus reaches supervisor	Relatively predictable
Hold leader	*Yes*	None	Predictable
Do nothing	*Yes*	None	Predictable

It is difficult to quantify many of the benefits that come from better information, but it is possible to estimate the benefit of some of them. Using conservative assumptions, using the PDAs to hold a bus' leader in response to moderately late buses would save 257,880 passenger minutes a year (see section 6.4.) This alone might not justify the system's estimated $232,640 cost (Tom Pleuger 2002,) but when taken as part of a significantly larger set of benefits is a strong indication of an investment that will bring positive return.

This assumes that certain aspects of the PDA rollout will go successfully, and notably that some existing procedural problems will be remedied. For instance, for the PDAs to track buses and allow supervisors to send messages, the central computer must be able to correctly identify what buses are operating on what runs. It can only do so if drivers log in correctly when starting their run and if buses are digitally assigned to the garages out of which they actually work. Presently, drivers do not always log in and some buses are not digitally assigned correctly. The PDAs will only be of benefit if these problems are addressed.

7.2 Conclusions

The method and model developed in this paper are a useful approach to the study of service management strategies, and are of potential use to transit agencies seeking to change their communication systems, the responsibilities of personnel, or both.

This thesis has applied a model of communications, information and responsibility to the Chicago Transit Authority. The model produced a logical and accurate representation of CTA as it is today, and a reasonable prediction of future changes. While the precision of the model's estimation of strain on communication channels is only fair, it is effective at giving estimates that appear reasonable. The method of determining what response techniques are or are not available shows useful insights into a strategy's strengths and weaknesses, and offers a framework for comparison between different approaches.

To apply this model to another agency, the following steps are necessary:

- The kinds of personnel must be updated, and the information and knowledge they already have must be entered.
- Communications channels must be replaced.
- The workflow must be changed. This is the most time-consuming part of the process. First one must determine what the standard operating procedures are for dealing with disruptions, and from that, what steps the agency goes through from the instance of a disruption to the execution of response techniques. Then the corresponding rows must be arranged in the model, and certain values checked to ensure that the process being entered is a feasible one. This information must be slightly modified for each proposed adjustment to the agency.
- The number of instances of each kind of disruption and each response technique during a given hour must be determined and entered.
- Finally, if the agency conducts business in a language other than English, one must listen to recordings of radio communication and mark the average time taken to relay each piece of information that the agency works with.

When planning to use new communication technology, an agency must develop new procedures simultaneously for the technology to have maximum benefit.

In studying the use of the Bus Emergency Communication System at CTA, it became clear that both its design and use suffer from a lack of understanding of the new procedures surrounding it. An example of its design suffering is that messages about equipment defects do not include some information a dispatcher needs to make a decision, while it does contain extraneous information. This means that a dispatcher must make a voice call every time he receives a digital message about an equipment defect, and the efficiency of digital messaging is lost. An example of its use suffering is that SOPs were not initially updated to reflect the use of the technology, and operators were not taught some basic facts such as which messages were for emergency use only. This means that a number of messages are sent erroneously and dispatchers must work through many emergency messages for non-emergency events. Fundamentally, failure to develop new procedures simultaneous to new communication technology will result in lost efficiencies and potentially serious problems. Better communications does not necessarily mean better operations, instead it allows for better procedures. It is those procedures that can mean better operations.

The strengths of voice communications, including ease of use and flexibility, make it well suited to communications on unpredictable service management tasks and tasks requiring collaboration.

Voice communication allows concerned parties to immediately relay whatever information they deem relevant, quickly draw others into communication, and collaborate on decisions. Digital messaging, in contrast, can send messages from a predetermined list quickly and requires typing for anything else, and removes nuances of speech that aide communication and collaboration. At CTA, digital messages from buses about equipment defects are followed up with voice communication, because it allows dispatchers the flexibility of learning the details they deem relevant and working with the bus operator to find the easiest solution to the problem.

The strengths of digital communications, including scalability, speed for simple messages and automation, make it well suited to communications on predictable service management tasks and tasks that peak.

Digital messaging can allow people to send the most common messages very quickly, as simply as pushing a button, and the message can be sent even if there is a lot of other communications traffic. Voice communication, by contrast, requires the user to wait for or request an available channel, get the attention of the message's recipient(s), and say the message. Some information can also be relayed without any action at all, as when a bus regularly transmits its location to a control center. If a problem is well understood, digital messaging can help people respond to the problem more quickly, and make the speed and reliability of communications more predictable and constant throughout the day. If a kind of disruption that peaks significantly is handled with communications over voice channels, those channels' availability for handling that disruption and other disruptions will lessen during peaks. If the disruption is handled with digital communications, both responses to it and responses to disruptions that are coordinated over a voice channel experience an improvement in reliability.

For digital messaging to be an effective medium for deciding on and implementing a response to a disruption, the procedures for doing so must be well understood and supported by the system of messages.

At CTA, bus drivers send digital messages with considerable detail about equipment failures, disturbances, even accidents. They are almost always followed by a voice call because information the dispatcher considers important cannot be sent digitally using CTA's system. Hypothetically almost any task can be accomplished using only digital messaging if the task is understood well enough. Chicago's 911 center handles much of its police dispatching digitally, but it does so with very sophisticated software that facilitates every aspect of the process, from the moment a call comes in and the phone number and location are entered automatically into the message that will go to the police car to the moment an officer enters the necessary information on how the problem was resolved and clears the problem from his list of tasks. So while digital messaging can potentially make a great many things easier, the level of detail necessary for complicated tasks – and the cost of learning that information and designing a digital system accordingly – can make automating them more complicated than it is worth.

The task of responding to incidents has a "natural home" in the control center.

Responding to emergencies or breakdowns requires the coordination of multiple mobile supervisors and repair trucks. To be done efficiently, this requires the coordination of different personnel to ensure even workloads and timely responses. For the mobile units to do this coordination effectively themselves would require that every person know the assignments of every other person, or that they would pause to discuss who is most appropriate for a task every time a new requirement arrives. One person can do this much more efficiently and effectively. As incidents occur randomly throughout the service area, this person gains nothing by being on the street. He would have first-hand knowledge of only a fraction of events. A control center is the logical place for this person to be, providing him with the resources that make the job easier: a desk, a computer, and protection from distraction.

The task of making schedule adjustments has a "natural home" in the field.

A supervisor standing on a route always has information that a dispatcher might not or can not have:

- The history of bus arrivals at that location
- The traffic conditions on that portion of the route
- The load of buses as they pass that location
- The understanding of a route that can come only by observing and interacting with it for weeks

He can also talk to bus operators in person. It is possible to provide a dispatcher with more technology or communications resources than a street supervisor, and this would give him an advantage. For example, if all buses transmitted their location to the control center but the information did not reach the street supervisors, the control center would have a better picture about the line as a whole. Similarly if buses and dispatchers had radios but supervisors did not, a dispatcher would have the ability to implement some responses a supervisor could not. But putting radios or digital messaging in buses costs far more than giving it to supervisors. Recall from chapter 2 that an agency has on the order of 1 supervisor for every 30 buses. Equipment for supervisors is typically cheaper than that for buses as it does not need to withstand the punishing vibrations of a bus. At CTA, each personal digital assistant is expected to cost less than half of a bus data terminal. So the marginal cost of extending communications technology to supervisors is comparatively small. Technologies being equal, street supervisors are better at making schedule adjustments than dispatchers can be.

Digital communication can supplement voice communication for a transit agency, but can never replace it.

There is a roughly inverse relationship between the frequency with which a disruption occurs and how well it is understood. No one can plan for every possible kind of disruption, teach everyone the procedures for handling it, and program every message into a digital message system. On September 11th, when many of Chicago's skyscrapers were evacuated, CTA had to provide unplanned service to evacuate the downtown area while watching for hints of suspicious activity so subtle that they would not usually be cause for concern. Recordings show dispatchers and supervisors working together over the radio, creating a strategy as they go along, and giving instructions to supervisors (including "find out which buildings are being evacuated") that could not possibly have been anticipated. This collaboration and instruction was all made possible with voice communication. Being restricted to digital messaging, no matter how thoroughly it was developed, would have been a substantial hindrance.

7.3 Future Work

7.3.1 Improving the Model

The usefulness of the model proposed in this thesis has been demonstrated, but the model is also ripe for improvement. The system of measuring the time to relay individual pieces of information was adequate for the study performed but does not appear to be robust. For example in section 6.4 the difference between the two PDA scenarios, in terms of predicted strain, is dominated by discussions on rescheduling the street. The capacity taken up by these discussions may have been overestimated due to the little data currently available for these discussions. A system based on measurements of actual messages, rather than deconstructing and recombining the pieces of information that make up those messages, might prove more accurate but would be considerably more labor-intensive. Another improvement would be a more detailed model of the stages of dispatching, such as choosing the most appropriate responder, giving an instruction, and receiving a report when the task is completed. A more sophisticated measure of capacity such as queuing theory could also be of benefit.

7.3.2 Developing a Better Understanding of the Costs and Benefits of Service Restoration Techniques

One limitation of this research was the absence of literature comparing the costs and benefits of different responses to disruptions. This made it difficult to determine the importance of a given response becoming available, or the benefits gained in providing decision-makers with enough information to choose between them effectively. Having a better understanding of the differences in using different response techniques would clearly be of benefit to service restoration and the study thereof.

7.3.3 Determining the Optimum Placement of Supervisors

CTA has most of its supervisors along the route and few of them at terminals. The MBTA takes the opposite approach. Broadly speaking, supervisors along the route have an advantage in keeping buses on schedule, while supervisors at terminals have an advantage at managing the route as a whole. It is unclear which has the greater impact on service, and it is unclear whether either of these advantages are strengthened or eliminated by new communication technologies. Answering these questions could lead to improved service, and the framework developed in this thesis could potentially be useful in doing so.

7.3.4 Efficiently Dividing Work Among Supervisors Along a Route

One topic not explored in this thesis is how a number of supervisors along a route can best divide responsibility to effectively manage it. A supervisor might manage buses up until and at the point where they pass him, at the point where they pass him and afterwards, for a certain distance around him, or even all the buses a given direction from him (whether they are approaching him or moving away.) As communication technology changes what a supervisor knows and does, determining how supervisors can best divide responsibility for a route becomes increasingly important.

7.3.5 Developing Digital Messaging Systems for Transit Tasks

As stated in section 7.2, digital messaging can help individuals deal with a problem more quickly, but only if the way the problem is dealt with is well understood. Starting with the fundamentals of dispatching, of managing an accident, of correcting delays, etc. one could create good digital messaging and computer support for these tasks. The framework presented in this thesis could be a good place to start for schedule and incident management, although less so for the act of dispatching itself. With support systems designed around the way transit agency employees actually respond to disruptions, their jobs could be made easier and their results more effective.

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Appendix A: Tables from Communications Model

All tables and figures are from the model of CTA as it is now, at the morning peak, after adjustment to account for communications capacity, unless otherwise noted.

Table A-2: Tasks Listed in "Required"

Bus early
Are more passengers likely to board?
Do nothing
Hold bus
Bus late (short headway)
What response is least disruptive?
Do nothing
Drop-off only
Express down a different street
Express to a later point
Follower picks up passengers
Hold leader prefol / hold leader
Short turn
Bus late (long headway)
Is bus so late that it is almost bunched?
What response is least disruptive?
Do nothing
Drop-off only
Express down a different street
Express to a later point
Follower picks up passengers
Short turn
Crush load
What response is least disruptive?
Do nothing
Drop-off only
Hold prefol / hold leader
Use standby bus
Mechanical problem (minor)
Can a supervisor repair it at terminal?
Can bus be taken out of service without disruption?
Do nothing
Jump buses
Operator exchange
Pull-in
Relief oper. Relieves other than scheduled oper.
Supervisor repairs bus at terminal
Mechanical problem (serious)
Can bus be removed from service without harm?
Can bus be replaced with standby?
How can bus be repaired or replaced?
(Extra) How can bus be replaced?
Jump buses
Maintenance brings bus change
Pull in/out
Relief oper. relieves other than scheduled oper.
Pull-in
Supervisor repairs bus on-site
Truck repairs bus on-site
Use standby bus
Mechanical problem (major)
How can bus be repaired or replaced?
Jump buses
Maint. tows bus
Maintenance brings bus change
Relief oper. relieves other than sched. oper.
Supervisor repairs bus on-site
Truck repairs bus on-site
Emergency / security / fare dispute
Are police and / or medics needed?
Is point supervision appropriate?
Bus continues to point supervision
Dispatch mobile supervision
Dispatch police and/or medics
Do not dispatch police or medics
Accident
Are police and/or medics needed?
Dispatch mobile supervision
Dispatch police
Dispatch police and medics
Operator misses relief
Are passengers stuck on bus?
Can relief operator get to garage or relief point?
Is jumping reliefs possible?
will jumping reliefs be possible later in the trip?
Continue in service
Jump reliefs
Pull in
Pull-out instead of relieve
Relief oper. relieves other than sched.
Relief oper. relieves scheduled oper. later
Stand bus
Blockage
Is reroute significantly longer?
Will blockage end soon?
Do nothing
Emergency reroute
Hold leader
See: unfilled run
Bus standing / service gap
Can we spread the interval?
Follower picks up passengers
Spread the interval
Spread the terminal until bus restored
Unfilled run
Can bus be borrowed?
Is a standby bus available?
Short-headway route?
Fill from another street
Fill with pull-in
Spread the terminal
Use standby bus
Unplanned bus bridge
Do some of each:
Emergency reroute I / II
Fill from another street
Fill with pull-in
Pull-out instead of relieve
Use standby bus
Congestion / Weather / Routewide crowding
Are more buses warranted?
Fill from another street
Fill with pull-in
Reschedule street
Use standby bus
Late pull-out
Un-spread the terminal
Put bus in place

Table A-3: Sample from "Required:" Information Necessary to Deal with a Late Bus (Short Headway)

	Area bus schedules	availability at garages	Bus schedule	Route demand profile	Route schedule	Street Geometry I	Street Geometry II	Supervisor & truck shifts	supervisors can fix	Bunched?	Bus location	Bus location @	Bus' lead headway	Existence of problem	Location of blockage	severity of issue	Relief whereabouts	Route bus locations	Status of other routes
Bus late (short headway)	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
What response is least disruptive?	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Do nothing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drop-off only	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Express down a different street	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
Express to a later point	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Follower picks up passengers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hold leader prefol / hold leader	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
Short turn	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0

Table A-4: Strain: Asking for Information

	Area bus schedules	availability at garages	Bus schedule	Route demand profile	Route schedule	Street Geometry I	Street Geometry II	Supervisor & truck shifts	supervisors can fix	Bunched?	Bus location	Bus location @	Bus' lead headway	Existence of problem	Location of blockage	severity of issue	Relief whereabouts	Route bus locations	Status of other routes	Instructions	Conversation overhead	Area bus schedules
1	Sup radio	0	4.5	5.5	5	5.5	2.5	5	2	8	3	4	2	2.5	4	3.75	7	4	5	6	0	0
2	Bus chan	0	4.5	5.5	5	5.5	2.5	5	2	8	3	0	0	2.5	4	3.75	7	4	5	6	0	100
3	Digital data	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Face to face	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A-5: Strain: Giving Information

	Area bus schedules	availability at garages	Bus schedule	Route demand profile	Route schedule	Street Geometry I	Street Geometry II	Supervisor & truck shifts	supervisors can fix	Bunched?	Bus location	Bus location @	Bus' lead headway	Existence of problem	Location of blockage	severity of issue	Relief whereabouts	Route bus locations	Status of other routes	Instructions	Conversation overhead	Area bus schedules
1	Sup radio	0	3	6	12	20	3	7	3	15	1	5	2	5	6.5	5	8	5	25	10	10	9.9
2	Bus chan	0	4.5	9	18	30	4.5	10.5	4.5	22.5	1.5	7.5	3	7.5	9.75	7.5	12	7.5	37.5	15	10	3.2
3	Digital data	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Face to face	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A-6: Strain: Asking for and Getting Information

	Area bus schedules	availability at garages	Bus schedule	Route demand profile	Route schedule	Street Geometry I	Street Geometry II	Supervisor & truck shifts	supervisors can fix	Bunched?	Bus location	Bus location @	Bus' lead headway	Existence of problem	Location of blockage	severity of issue	Relief whereabouts	Route bus locations	Status of other routes	Instructions	Conversation overhead	Area bus schedules
1	Sup radio	0	7.5	11.5	17	25.5	5.5	12	5	23	4	9	4	7.5	10.5	8.75	15	9	30	16	10	9.9
2	Bus chan	0	9	14.5	23	35.5	7	15.5	6.5	30.5	4.5	7.5	3	10	13.75	11.25	19	11.5	42.5	21	10	103.2
3	Digital data	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Face to face	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A-7: Strain: What Information Can Go Over what Channels

	Area bus schedules	availability at garages	Bus schedule	Route demand profile	Route schedule	Street Geometry I	Street Geometry II	Supervisor & truck shifts	supervisors can fix	Bunched?	Bus location	Bus location @	Bus' lead headway	Existence of problem	Location of blockage	severity of issue	Relief whereabouts	Route bus locations	Status of other routes	Instructions	Conversation overhead	Area bus schedules
1	Sup radio	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
2	Bus chan	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
3	Digital data	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
4	Face to face	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE

A-8: Conversations: All Phases and Steps

Table A-8.1: Bus Early

Frequency	Step	Step detail	Channel	#	Actor
	Early bus				
10	Given information				
10	Awareness			1	Bus operator
10	Are more passengers likely to board?	Needed		1	Bus operator
10	Are more passengers likely to board?	Needed and unknown		1	Bus operator
2	Do nothing			1	Bus operator
8	Hold bus	Needed		1	Bus operator
8	Hold bus	Needed and unknown			

Table A-8.2: Bus Late (Short Headway)

Frequency	Step	Step detail	Channel	#	Actor
	Bus late (short head)				
12					
12	Awareness			1	Bus operator
12	Reports to C/PCC		2	1	Bus operator
12	Reports to supervision		1	6	Point supervisor
12	Known by supervision			6	Point supervisor
12	What response is least disruptive?	Needed			
	What response is least disruptive?	Needed and unknown		6	Point supervisor
	Do nothing				
	Drop-off only	Needed			
	Drop-off only	Needed and unknown			
	Drop-off only	Instructs	4	6	Point supervisor
	Drop-off only	Announces	1	6	Point supervisor
	Express down a different street	Needed			
	Express down a different street	Needed and unknown			
	Express down a different street	Instructs	4	6	Point supervisor
	Express down a different street	Announces	1	6	Point supervisor
	Express to a later point	Needed			
	Express to a later point	Needed and unknown			
	Express to a later point	Instructs	4	6	Point supervisor
	Express to a later point	Announces	1	6	Point supervisor
0	Follower picks up passengers	Needed			
0	Follower picks up passengers	Needed and unknown			
0	Follower picks up passengers	Instructs	4	6	Point supervisor
	Hold leader prefol / hold leader	Needed			
	Hold leader prefol / hold leader	Needed and unknown			
	Hold leader prefol / hold leader	Instructs	4	6	Point supervisor
	Hold leader prefol / hold leader	Announces	1	6	Point supervisor
	Short turn	Needed			
	Short turn	Needed and unknown			
	Short turn	Instructs	4	6	Point supervisor
	Short turn	Announces	1	6	Point supervisor

Table A-8.3: Bus Late (Long Headway)

Frequency	Step	Step detail	Channel	#	Actor
	Bus late (long headway)				
6	Awareness			1	Bus operator
6	Reports to C/PCC		3		
6	Reports to supervision		1		
6	Known by supervision				
	Is bus so late it's bunching?	Needed			
	Is bus so late it's bunching?	Needed and unknown			
	What response is least disruptive?	Needed			
	What response is least disruptive?	Needed and unknown			
	Do nothing	Needed			
0	Drop-off only	Needed			
0	Drop-off only	Needed and unknown			
0	Drop-off only	Instructs	4	6	Point supervisor
0	Drop-off only	Announces	1	6	Point supervisor
0	Express down a different street	Needed			
0	Express down a different street	Needed and unknown			
0	Express down a different street	Instructs	4	6	Point supervisor
0	Express down a different street	Announces	1	6	Point supervisor
0	Express to a later point	Needed			
0	Express to a later point	Needed and unknown			
0	Express to a later point	Instructs	4	6	Point supervisor
0	Express to a later point	Announces	1	6	Point supervisor
	Follower picks up passengers	Needed			
	Follower picks up passengers	Needed and unknown			
	Follower picks up passengers	Instructs	4	6	Point supervisor
	Short turn	Needed			
	Short turn	Needed and unknown			
	Short turn	Instructs	4	6	Point supervisor
	Short turn	Announces	1	6	Point supervisor

Table A-8.4: Crush Load

Frequency	Step	Step detail	Channel	#	Actor
	Crush load				
1	Awareness			1	Bus operator
1	Reports to C/PCC		3	1	Bus operator
	Reports to supervision		1	6	Point supervisor
	Known by supervision				
	What response is least disruptive?	Needed			
	What response is least disruptive?	Needed and unknown			
0	Do nothing				
0	Drop-off only	Needed			
0	Drop-off only	Needed and unknown			
0	Drop-off only	Instructs	4	6	Point supervisor
0	Drop-off only	Announces	1	6	Point supervisor
	Hold prefol / hold leader	Needed			
	Hold prefol / hold leader	Needed and unknown			
	Hold prefol / hold leader	Instructs	4	6	Point supervisor
	Hold prefol / hold leader	Announces	1	6	Point supervisor

Table A-8.5: Mechanical Problem (Minor)

Frequency	Step	Step detail	Channel	#	Actor
6	Awareness			1	Bus operator
6	Reports to C/PCC		3	1	Bus operator
6	C/PCC asks for detail		2	3	Controller
6	Known by controller			3	Controller
6	Can a supervisor repair it at terminal?	Needed		3	Controller
6	Can a supervisor repair it at terminal?	Needed and unknown		3	Controller
4	Supervisor repairs bus at terminal	Needed			
4	Supervisor repairs bus at terminal	Needed and unknown			
4	Supervisor repairs bus at terminal	Instructs	1	3	Controller
2	Can bus be taken out of service without disruption?	Needed			
2	Can bus be taken out of service without disruption?	Needed and unknown			
1	Do nothing				
4	Jump buses	Needed			
4	Jump buses	Needed and unknown			
4	Jump buses	Instructs	2	3	Controller
4	Jump buses	Announces	1	3	Controller
1	Operator exchange	Needed			
1	Operator exchange	Needed and unknown			
1	Operator exchange	Instructs	2	3	Controller
1	Operator exchange	Announces	1	3	Controller
0	Pull-in	Needed			
0	Pull-in	Needed and unknown			
0	Pull-in	Instructs	2	3	Controller
0	Relief oper. Relieves other than scheduled oper.	Needed			
0	Relief oper. Relieves other than scheduled oper.	Needed and unknown			
0	Relief oper. Relieves other than scheduled oper.	Announces & Instructs	1	3	Controller

Table A-8.6: Mechanical Problem (Serious)

Frequency	Step	Step detail	Channel	#	Actor
2	Awareness			1	Bus operator
2	Reports to C/PCC		3	1	Bus operator
2	C/PCC asks for detail		2	3	Controller
2	Known by controller			3	Controller
2	Can bus be removed from service w/o harm?	Needed			
2	Can bus be removed from service w/o harm?	Needed and unknown			
0	Pull-in	Needed			
0	Pull-in	Needed and unknown			
0	Pull-in	Instructs	2	3	Controller
0	Relief oper. Relieves other than scheduled oper.	Needed			
0	Relief oper. Relieves other than scheduled oper.	Needed and unknown			
0	Relief oper. Relieves other than scheduled oper.	Announces & Instructs	1	3	Controller
2	Jump buses	Needed			
2	Jump buses	Needed and unknown			
2	Jump buses	Instructs	2	3	Controller
2	Jump buses	Announces	1	3	Controller
2	How can bus be repaired or replaced?	Needed			
2	How can bus be repaired or replaced?	Needed and unknown			
2	Supervisor repairs bus on-site	Needed			
2	Supervisor repairs bus on-site	Needed and unknown			
2	Supervisor repairs bus on-site	Announces & Instructs	1	3	Controller
0	Truck repairs bus on-site	Needed			
0	Truck repairs bus on-site	Needed and unknown			
0	Truck repairs bus on-site	Announces & Instructs	1	3	Controller
0	Maintenance brings bus change	Needed			
0	Maintenance brings bus change	Needed and unknown			
0	Maintenance brings bus change	Announces & Instructs	1	3	Controller
1	Pull in/out	Needed			
1	Pull in/out	Needed and unknown			
1	Pull in/out	Instructs	2	3	Controller
1	Pull in/out	Announces	1	3	Controller

Table A-8.7: Mechanical Problem (Major)

Frequency	Step	Step detail	Channel	#	Actor
	Mechanical problem (major)				
12	Awareness			1	Bus operator
12	Reports to C/PCC		3	1	Bus operator
12	C/PCC asks for detail		2	3	Controller
12	Known by controller			3	Controller
12	Jump buses	Needed			
12	Jump buses	Needed and unknown			
12	Jump buses	Instructs	2	3	Controller
12	How can bus be repaired or replaced?	Needed			
12	How can bus be repaired or replaced?	Needed and unknown			
2	Supervisor repairs bus on-site	Needed			
2	Supervisor repairs bus on-site	Needed and unknown			
2	Supervisor repairs bus on-site	Announces & Instructs	1	3	Controller
8	Truck repairs bus on-site	Needed			
8	Truck repairs bus on-site	Needed and unknown			
8	Truck repairs bus on-site	Announces & Instructs	1	3	Controller
0	Maintenance brings bus change	Needed			
0	Maintenance brings bus change	Needed and unknown			
0	Maintenance brings bus change	Announces & Instructs	1	3	Controller
0	Relief oper. relieves other than sched. oper.	Needed			
0	Relief oper. relieves other than sched. oper.	Needed and unknown			
0	Relief oper. relieves other than sched. oper.	Announces & Instructs	1	3	Controller
2	Maint. tows bus	Needed			
2	Maint. tows bus	Needed and unknown			
2	Maint. tows bus	Announces & Instructs	1	3	Controller

Table A-8.8: Emergency / Security / Fare dispute

Frequency	Step	Step detail	Channel	#	Actor
2	Emergency / security / fare dispute				
2	Awareness			1	Bus operator
2	Reports to C/PCC		3	1	Bus operator
2	C/PCC asks for detail		2	3	Controller
2	Known by controller			3	Controller
2	Are police and / or medics needed?	Needed			
2	Are police and / or medics needed?	Needed and unknown			
2	Is point supervision appropriate?	Needed			
2	Is point supervision appropriate?	Needed and unknown			
1	Bus continues to point supervision	Needed			
1	Bus continues to point supervision	Needed and unknown			
1	Bus continues to point supervision	Instructs	2	3	Controller
1	Bus continues to point supervision	Announces	1	3	Controller
1	Dispatch mobile supervision	Needed			
1	Dispatch mobile supervision	Needed and unknown			
1	Dispatch mobile supervision	Announces & Instructs	1	3	Controller
	Dispatch police and/or medics	Needed			
	Dispatch police and/or medics	Needed and unknown			
	Dispatch police and/or medics	Instructs	5	3	Controller
	Dispatch police and/or medics	Announces	1	3	Controller
	Do not dispatch police or medics				

Table A-8.9: Accident

Frequency	Step	Step detail	Channel	#	Actor
	Accident				
2	Awareness			1	Bus operator
2	Reports to C/PCC		3	1	Bus operator
2	C/PCC asks for detail		2	3	Controller
2	Known by controller			3	Controller
2	Are police and/or medics needed?	Needed			
2	Are police and/or medics needed?	Needed and unknown			
2	Dispatch mobile supervision	Needed			
2	Dispatch mobile supervision	Needed and unknown			
2	Dispatch mobile supervision	Announces & Instructs	1	3	Controller
1	Dispatch police	Instructs	5	3	Controller
1	Dispatch police and medics	Instructs	5	3	Controller
	Operator misses relief				
0	Awareness			1	Bus operator
0	Reports to C/PCC		3	1	Bus operator
0	C/PCC asks for detail		2	3	Controller
0	Known by controller			3	Controller
0	Reports to supervision		1		
0	Known by supervision				
0	Is jumping reliefs possible?	Needed			
0	Is jumping reliefs possible?	Needed and unknown			
0	Jump reliefs	Needed			
0	Jump reliefs	Needed and unknown			
0	Jump reliefs	Instructs	4		
0	Jump reliefs	Announces	1		

Table A-8.10: Operator Misses Relief

Frequency	Step	Step detail	Channel	#	Actor
0	Awareness			1	Bus operator
0	Reports to C/PCC		3	1	Bus operator
0	C/PCC asks for detail		2	3	Controller
0	Known by controller			3	Controller
0	Reports to supervision		1		
0	Known by supervision				
0	Is jumping reliefs possible?	Needed			
0	Is jumping reliefs possible?	Needed and unknown			
0	Jump reliefs	Needed			
0	Jump reliefs	Needed and unknown			
0	Jump reliefs	Instructs	4		
0	Jump reliefs	Announces	1		

Table A-8.11: Blockage

Frequency	Step	Step detail	Channel	#	Actor
	Blockage				
2	Awareness			1	Bus operator
2	Reports to C/PCC		3	1	Bus operator
2	C/PCC asks for detail		2	3	Controller
2	Known by controller			3	Controller
2	Will blockage end soon?	Needed			
2	Will blockage end soon?	Needed and unknown			
1	Can bus reroute itself?		2	3	Controller
1	Self-reroute		2	3	Controller
2	Reports to supervision		1	3	Controller
2	Known by mobile supervisor				
2	Emergency reroute	Needed			
2	Emergency reroute	Needed and unknown			
2	Emergency reroute	Instructs	4	5	Mob. Sup.
2	Is reroute significantly longer?	Needed		5	Mob. Sup.
2	Is reroute significantly longer?	Needed and unknown		5	Mob. Sup.
	See also: unfilled run				

Table A-8.12: Bus Standing / Service Gap

Frequency	Step	Step detail	Channel	#	Actor
	Bus standing / service gap				
26	Informed		1	5	Supervisor
10	Spread the terminal	Needed			
10	Spread the terminal	Needed and unknown			
10	Spread the terminal	Instructs	4	5	Supervisor
10	Spread the terminal	Announces	1	5	Supervisor

Table A-8.13: Unfilled Run

Frequency	Step	Step detail	Channel	#	Actor
	Unfilled run				
22	Informed		1	5	Supervisor
22	Known by supervisor			5	Supervisor
22	Short-headway route?	Needed			
22	Short-headway route?	Needed and unknown			
8	Can bus be borrowed?	Needed			
8	Can bus be borrowed?	Needed and unknown			
8	Can bus be borrowed?	Inquiry	1	5	Supervisor
4	Fill from another street	Instruct	1	5	Supervisor
4	Fill from another street	Instruct	4	5	Supervisor
0	Fill with pull-in	Instruct	1	5	Supervisor
0	Fill with pull-in	Instruct	4	5	Supervisor
	See also: bus standing / service gap				

Table A-8.14: Unplanned Bus Bridge

Frequency	Step	Step detail	Channel	#	Actor
	Unplanned bus bridge				
0	Awareness			3	Controller
0	Dispatch mobile supervision		1	3	Controller
0	Known by mobile supervision				
0	Order buses		1	3	Controller
0	Emergency reroute			4	Mobile supervisor
0	Coordinate schedules			1	Mobile supervisor
0	See also: bus standing / service gap				

Table A-8.15: Congestion / Weather / Routewide Crowding

Frequency	Step	Step detail	Channel	#	Actor
	Congestion / Weather / Routewide crowding				
2	Awareness				Bus operator
2	Reports to C/PCC			3	Bus operator
2	C/PCC asks for detail		2	3	Controller
2	Reports to supervision		1	3	Controller
2	Known by supervision			6	Point supervisor
2	Reschedule street	Needed		6	Point supervisor
2	Reschedule street	Needed and unknown		6	Point supervisor
2	Reschedule street	Instructs	4	6	Point supervisor
2	Reschedule street	Announces	1	6	Point supervisor

Table A-8.16: Late Pull-out

Frequency	Step	Step detail	Channel	#	Actor
	Late pull-out				
4	Awareness				Garage
4	Reports to supervision		1		
4	Known by supervision				
4	Un-spread the terminal	Needed			
4	Un-spread the terminal	Needed and unknown			
4	Un-spread the terminal	Instruct	4		
4	Un-spread the terminal	Announces	1		

Table A-9: Full Detail: Bus Late (Short Headway)

	Step	Step detail	Channel		Actor	Total	Area bus schedules	Bus availability at garages	Bus schedule	Route demand profile	Route schedule	Street Geometry I	Street Geometry II	Supervisor & truck shifts	What supervisors can fix	Bunched?	Bus location	Bus location @	Bus' lead headway	Existence of problem	Location of blockage	Nature & severity of issue	Relief whereabouts	Route bus locations	Status of other routes	Instructions	Conversation overhead
12	Bus late (short head)					0																					
12	Awareness			1	Bus operator	2	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0		
12	Reports to C/PCC		2	1	Bus operator	2	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0		1
12	Reports to supervision		1	6	Point supervisor	2	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0		1
12	Known by supervision			6	Point supervisor	13	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	0	0		
12	What response is least disruptive?	Needed				3	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0		
	What response is least disruptive?	Needed and unknown		6	Point supervisor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Do nothing					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Drop-off only	Needed				2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Drop-off only	Needed and unknown				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Drop-off only	Instructs	4	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Drop-off only	Announces	1	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Express down a different street	Needed				4	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0		
	Express down a different street	Needed and unknown				1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0		
	Express down a different street	Instructs	4	6	Point supervisor	3	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Express down a different street	Announces	1	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Express to a later point	Needed				2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Express to a later point	Needed and unknown				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Express to a later point	Instructs	4	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Express to a later point	Announces	1	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
0	Follower picks up passengers	Needed				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
0	Follower picks up passengers	Needed and unknown				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
0	Follower picks up passengers	Instructs	4	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Hold leader prefol / hold leader	Needed				2	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1
	Hold leader prefol / hold leader	Needed and unknown				1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0		
	Hold leader prefol / hold leader	Instructs	4	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Hold leader prefol / hold leader	Announces	1	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Short turn	Needed				4	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0		
	Short turn	Needed and unknown				1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0		
	Short turn	Instructs	4	6	Point supervisor	2	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
	Short turn	Announces	1	6	Point supervisor	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1

Table A-10: Resulting Demand

Channel	Sum (minutes)	Sum (seconds)	Area bus schedules	Bus availability at garages	Bus schedule	Route demand profile	Route schedule	Street Geometry I	Street Geometry II	Supervisor & truck shifts	What supervisors can fix	Bunched?	Bus location	Bus location @	Bus' lead headway	Existence of problem	Location of blockage	Nature & severity of issue	Relief whereabouts	Route bus locations	Status of other routes	Instructions	Conversation overhead
Sup	57.9	3476.3	0	0	0	0	306	0	0	0	0	0	405	0	0	1102.5	17.5	465	0	0	128	290	762.3
Bus	83.6	5014.3	0	0	0	0	0	0	0	0	0	0	112.5	72	0	550	0	551	0	0	0	220	3508.8

	Demand	Supply	% used
Sup	3476.3	4752	97%
Bus	5014.3	8433	59%

Table A-11: Summary of Results from Different Scenarios

	8-9AM	3-4PM
Observed	about 100%	87%
Initial prediction	116%	101%
Adjusted prediction	97%	89%
PDA with announcements	78%	71%
PDA without announcements	52%	50%

Figure A-1: Use of Communication: Simulated, Supervisor Channels, 8-9AM

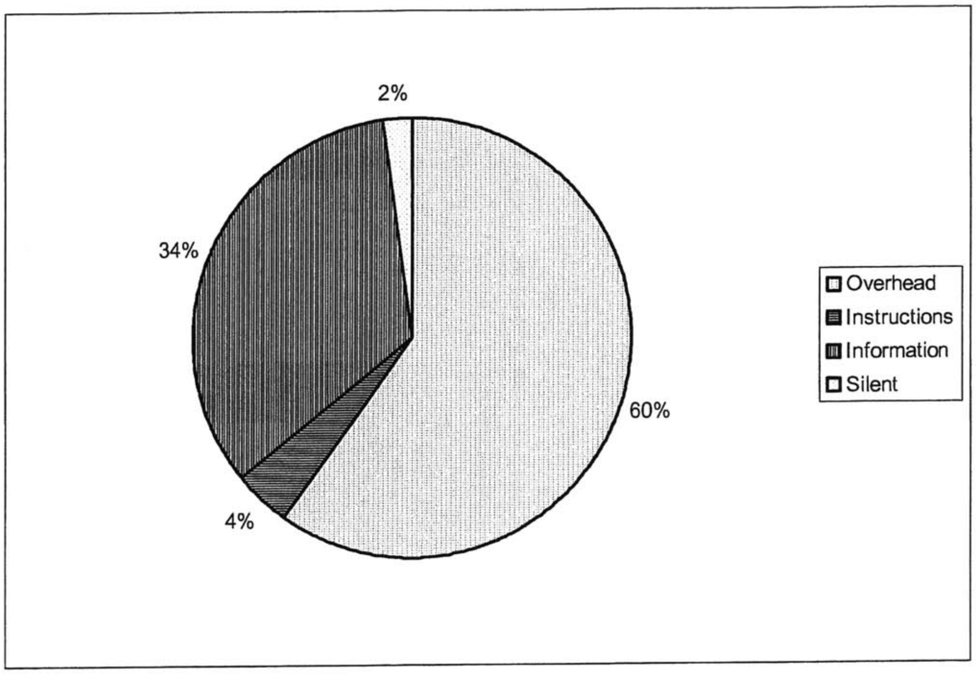
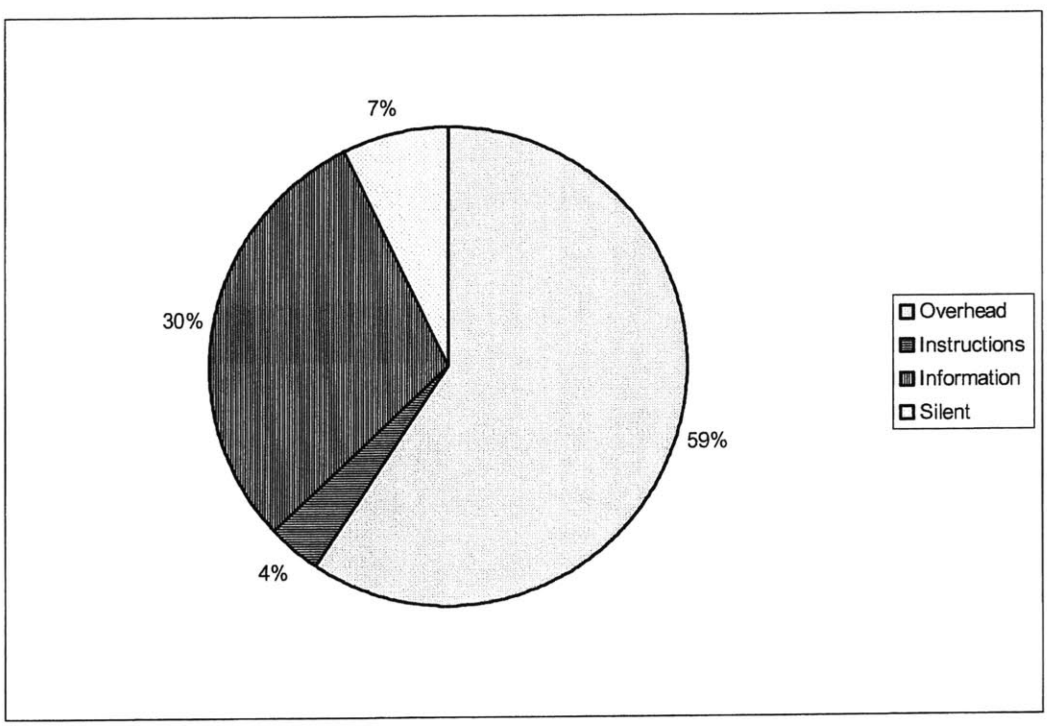


Figure A-2: Use of Communication: Simulated, Supervisor Channels, 3-4PM



Appendix B: CTA Operations Data

B.1: Data from the CTA BECS Database

Figures 1 through 5 are representations of data from the Chicago Transit Authority's BECS database, and were derived from using Microsoft Excel to manipulate and make graphs from the result of SQL (Structured Query Language) queries. Figures 1, 2 and 3 are from data that is permanently archived. Figures 4 and 5 are from data that is archived for 1 to 2 months.

Figure B-1: Disruption Volume Throughout Year

The three axes are week of the year (X), day of the week (Y), and disruptions in the day (Z.) The data is from September 1, 2000 to September 1, 2001. The two peaks next to each other are snowstorms December 11 and 13, 2000, while the third peak was a major flood on August 2, 2001.

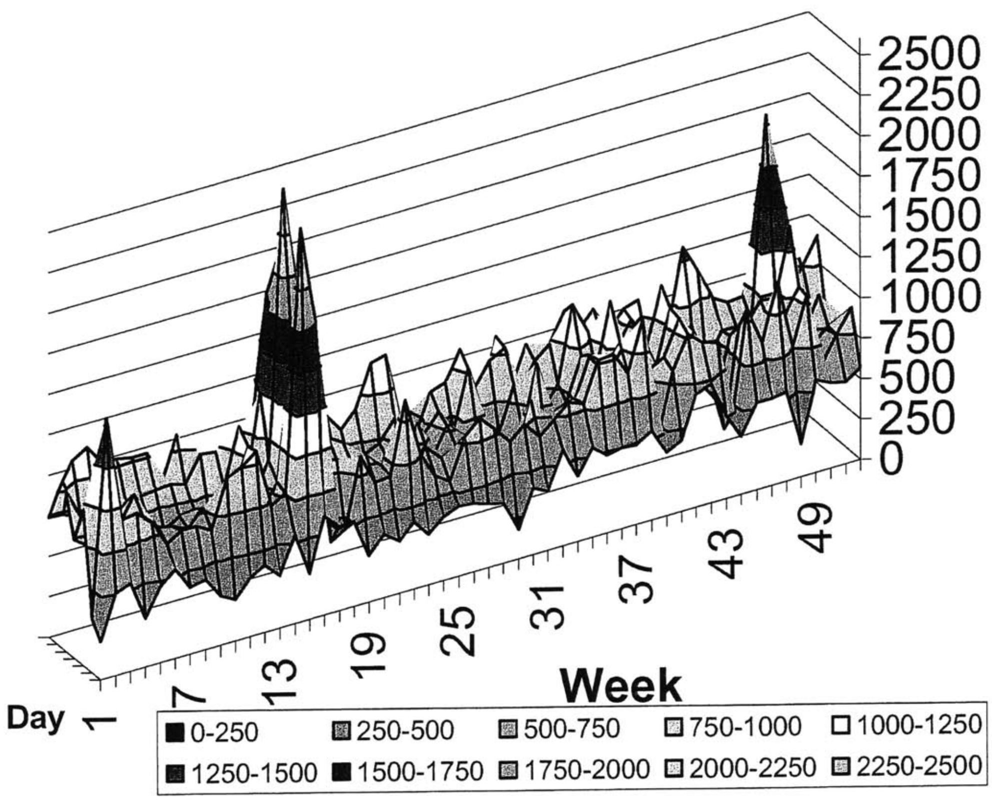


Figure B-2: Disruption Volume Throughout Week

The two axes show the hour of the week (X) and the average number of disruptions per hour (Y.) This data is average from September 1, 2000 to September 1, 2001.

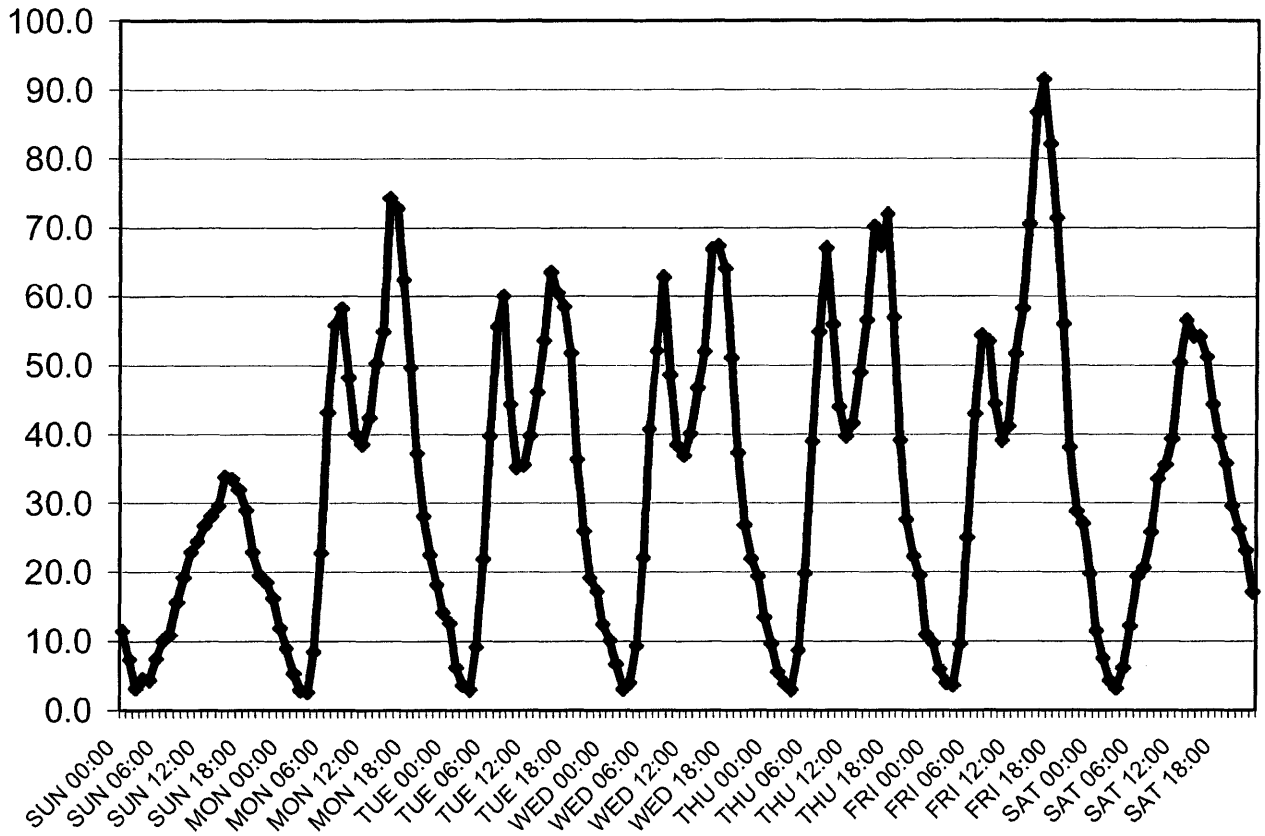


Figure B-3: Disruption Volume Throughout Day

The two axes show the hour of the day (X) and the average number of disruptions per hour (Y.) This data is average from Wednesdays between September 1, 2000 and September 1, 2001.

Some events are listed within the database under the generic heading of talk request or priority talk request. This occurs when a driver chooses to push the "Request to talk" or the "Priority request to talk" button instead of sending a digital message, usually because of unfamiliarity with the mobile data terminal's menus. To rectify this, talk request time was distributed among bus delay, mechanical problem, emergency, accident, missed relief, blockage, and congestion according to the existing proportion of those conditions. Priority talk requests were distributed between emergency and accident according to the existing proportion of those conditions.

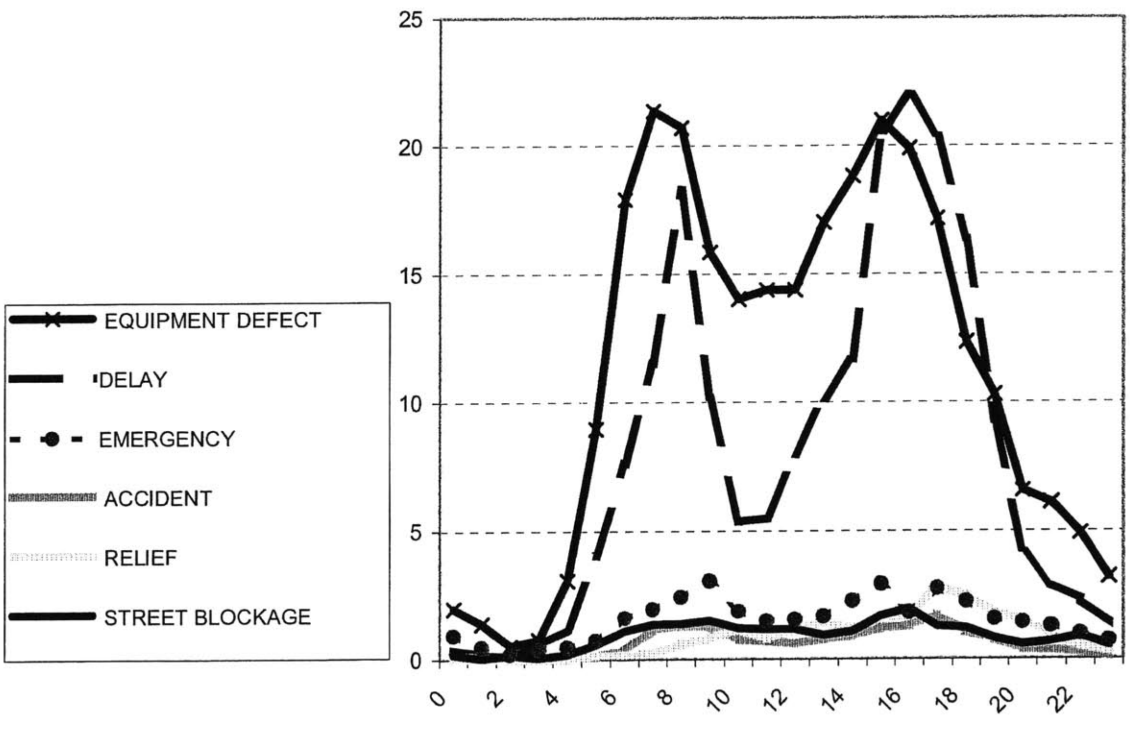


Figure B-4: Average Control Center Response Time to Delays

The lower bound is the time it takes the controller who receives the message to send it to the C1 controller, who will announce it to supervisors. The upper bound is the time it takes the C1 controller to delete the message from his computer after he has announced it. A small number of outliers may be included in the lower bound, specifically duplicate delay reports that are not announced over the air at all; however this data is corroborated by extensive personal observation. This data is averaged from Monday, November 19, through Thursday, November 22, 2001.

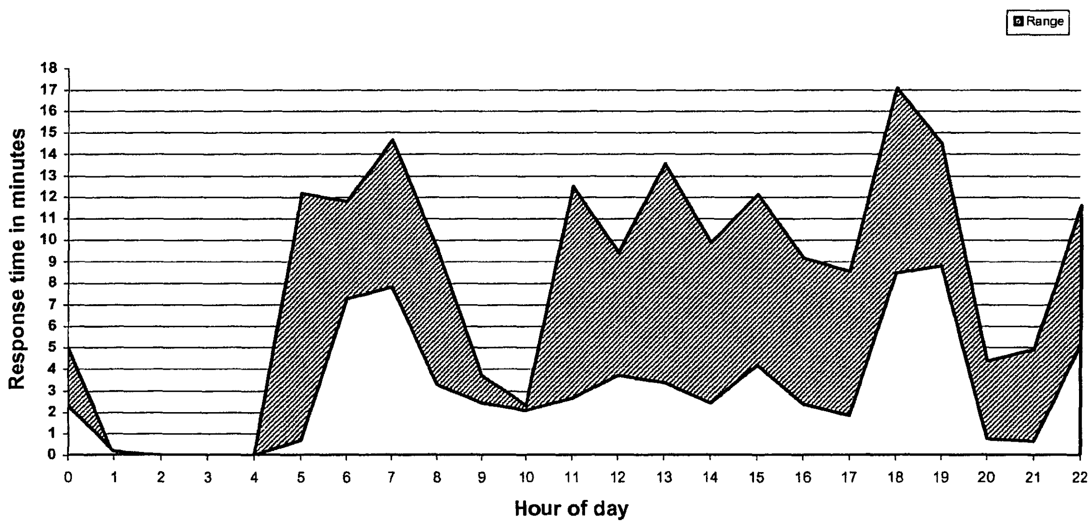
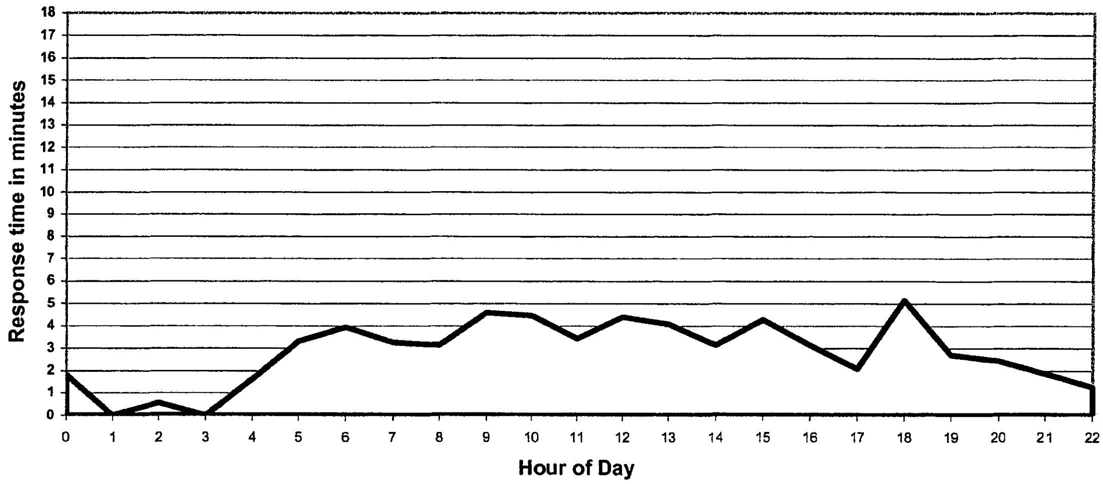


Figure B-5: Average Control Center Response Time to Equipment Defects

This graph shows only a lower bound, the time it takes the controller who receives the message to send it to the C1 controller, who will announce it to supervisors. No upper bound is available. This data is averaged from Monday, November 19, through Thursday, November 22, 2001.



B.2: Data Gathering from CTA Radio Recordings

The author listened to recordings of CTA's two supervisor channels and bus channels with audio editing software. He divided the conversations into individual pieces of information being relayed and recorded their start and ending time. The recordings were from September 10, 2001, including 8 to 8:30AM, 11 to 11:30 AM, and 3 to 3:30 PM.

Figure B-6: Time spent per Aspect of Communication

The data is from 3 to 3:30PM, Monday, September 10, 2001, on CTA's primary supervisory radio channel.

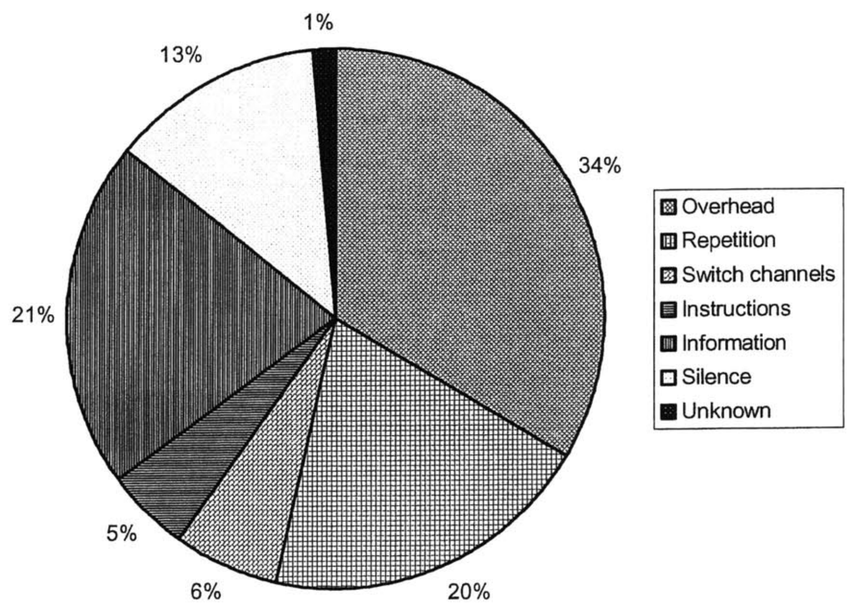


Table B-1: Average Time to Make Statements

The data is from supervisory channel recordings. Only statements that were made three or more times and were relatively consistent in length are shown.

Statement	Length (seconds)
Bus schedule	5
Supervisor & truck shifts	7
Bus location @	5
Location of blockage	5
Nature & severity of issue	6.5
asking for Bus schedule	5.5
asking for Route schedule	5.5
asking for Supervisor & truck shifts	2
asking for Bus location 4	3.6
asking for Existence of problem	3
asking for Location of blockage	3.6
asking for Nature & severity of issue	3
RTT	2.7
Go with message	3.3
Ten sixty-five	3.2
Asking situation	3
Giving instructions	9.8
Your attention	3.6

Table B-2: Sample of Communication

The following table shows the content of conversations on CTA's primary supervisor radio channel from 3:00 to 3:10PM, September 10, 2001.

Time (seconds)			Sender and receivers			Contents of message		
Start	End	Length	Speaker	Listener	FYI	Disruption	Intervention	Message
13	17	4	1	Control				10-4
17	20	3	2	Control				10-4
20	31	11	Control	3			See street supervision	Instructing street supervisor to see bus as it passes
31	39	8	3	Control			See street supervision	10-4
39	44	5	3	Control			See street supervision	Gives schedule information
44	45	1	Control	3			See street supervision	10-4
45	52	7	Control	4	5		Pull in/out	Informs supervision: run will pull in/out
52	55	3	4	Control			Pull in/out	10-4
55	58	3	5	Control			Pull in/out	10-4
58	62	4	6	Control			Pull in/out	10-4
62	66	4	6	Control			Spread interval	Informs control: he is spreading the interval
66	67	1	Control	6			Spread interval	10-4
67	83	16	Silence					
83	86	3	7	Control		Bus alarm	Intercept with mobile supervision	Requests to talk
86	90	4	Control	7		Bus alarm	Intercept with mobile supervision	Go with message
90	98	8	7	Control		Bus alarm	Intercept with mobile supervision	Corrects run number given by control
98	105	7	Control	7		Bus alarm	Intercept with mobile supervision	Confirms correction
105	106	1	7	Control		Bus alarm	Intercept with mobile supervision	10-4
106	113	7	7	8		Bus alarm	Intercept with mobile supervision	Asks to switch to alternate radio channel
113	119	6	8	7		Bus alarm	Intercept with mobile supervision	10-4
119	124	5	Control	9	10, 11, 12	Mechanical defect	Repair on-site	Requests to talk
124	133	9	Control	9	10, 11, 12	Mechanical defect	Repair on-site	Instructing street supervisor to see bus as it passes
133	135	2	9	Control		Mechanical defect	Repair on-site	10-4

Table B-2 continued

Time (seconds)			Senders and receivers			Contents of message		
Start	End	Length	Speaker	Listener	FYI	Disruption	Intervention	Message
135	140	5	?	Control		Mechanical defect	Repair on-site	10-4
140	149	9	13	Control				[Unintelligible]
149	152	3	Control	13				10-4
152	161	9	14	15				Requests to talk
161	181	20	14	15				Repeating
181	191	10	Control	16	17	Mechanical defect	Bus trade & Repair on-site	Requests to talk
191	204	13	Control	16	17	Mechanical defect	Bus trade & Repair on-site	Informs supervision of intervention
204	207	3	51	Control		Mechanical defect	Bus trade & Repair on-site	10-4
207	209	2	16	Control		Mechanical defect	Bus trade & Repair on-site	10-4
209	217	8	Control		17, 16, 18, 19, 20	Mechanical defect	Route management	Instructs supervision to manage route
217	222	5	?	Control		Mechanical defect	Route management	10-4
222	249	27	Control	?		Mechanical defect	Route management	Repeating
249	255	6	21	20		Mechanical defect	Route management	Asks to switch to alternate radio channel
255	278	23	Silence					
278	284	6	109	3				Requests to talk
284	288	4	3	109				Asks to switch to alternate radio channel
288	296	8	?	7				Asks to switch to alternate radio channel
296	302	6	7	?				10-4
302	312	10	Silence					
312	313	1	Control	5		Accident (supervisor car)	Reporting	Requests to talk
313	316	3	Control	5		Accident (supervisor car)	Reporting	Gives time and place of incident
316	322	6	Control	5		Accident (supervisor car)	Reporting	Gives nature of incident
322	326	4	5	Control		Accident (supervisor car)	Reporting	10-4
326	340	14	Silence					
340	342	2	5	22				Requests to talk

Table B-2 continued

Time (seconds)			Sender and receivers			Contents of message		
Start	End	Length	Speaker	Listener	FYI	Disruption	Intervention	Message
342	354	12	21	23				Asks to switch to alternate radio channel
354	363	9	5	22				Repeating
363	370	7	Control	24		Unexplained bus message	See street supervision	Requests to talk
370	376	6	Control	24		Unexplained bus message	See street supervision	Instructs supervisor to see bus as it passes
376	382	6	Control	24		Unexplained bus message	See street supervision	Detailing situation
382	396	14	Control	24		Unexplained bus message	See street supervision	Repeating
396	397	1	Control	3		Unexplained bus message	See street supervision	Requests to talk
397	406	9	?	Control		Unexplained bus message	See street supervision	Repeating
406	414	8	11	Control		Delay / missed relief	Relief management	Requests to talk
414	416	2	Control	11		Delay / missed relief	Relief management	Go with message
416	422	6	Control	11		Delay / missed relief	Relief management	Repeating
422	431	9	11	Control		Delay / missed relief	Relief management	Detailing relief management
431	432	1	Control		18	Delay / missed relief	Relief management	Your attention
432	445	13	Control	11		Delay / missed relief	Relief management	Repeating
445	447	2	11	Control		Delay / missed relief	Relief management	10-4
447	452	5	11	Control		Delay / missed relief	Relief management	Detailing relief management
452	455	3	Control	11		Delay / missed relief	Relief management	10-4
455	457	2	25	Control				Requests to talk
457	462	5	Control	20		Mechanical defect	Bus trade & pull-in	Requests to talk
462	468	6	Control	20		Mechanical defect	Bus trade & pull-in	Describes situation
468	473	5	Control	Control		Mechanical defect	Bus trade & pull-in	Instructs supervisor to instruct operator to trade busses
473	480	7	Control	Control		Mechanical defect	Bus trade & pull-in	Repeating
480	482	2	20?	Control		Mechanical defect	Bus trade & pull-in	10-4
482	485	3	Control	9		Schedule adherence	Follow-up	Go with message
485	490	5	9	Control		Schedule adherence	Follow-up	No message
490	492	2	25	Control		Schedule adherence	Follow-up	Requests to talk

Table B-2 continued

Time (seconds)			Sender and receivers			Contents of message		
Start	End	Length	Speaker	Listener	FYI	Disruption	Intervention	Message
492	497	5	Control	25		Schedule adherence	Follow-up	Go with message
497	503	6	25	Control		Schedule adherence	Follow-up	Asks if service restoration action has occurred
503	513	10	25	Control		Schedule adherence	Follow-up	Repeating
513	515	2	Control	25		Schedule adherence	Follow-up	Has no information
515	519	4	26	25		Schedule adherence	Follow-up	Asks to switch to alternate radio channel
519	522	3	25	26		Schedule adherence	Follow-up	10-4
522	525	3	?	24				Requests to talk
525	530	5	27	3				Asks to switch to alternate radio channel
530	531	1	3	27				10-4
531	534	3	16	Control			Reporting COA	Requests to talk
534	536	2	Control	16			Reporting COA	Go with message
536	542	6	16	Control			Reporting COA	Reports that problem was clear on arrival
542	544	2	Control	16			Reporting COA	10-4
544	546	2	Control		29		Reporting COA	Your attention
546	561	15	Silence					
561	564	3	28	Control				Reports that he is now on duty
564	566	2	Control	28				10-4
566	570	4	?	Control				Requests to talk
570	573	3	?	30				Asks to switch to alternate radio channel
573	579	6	Control	31		Mechanical defect	Bus trade	Requests to talk
579	584	5	Control	31		Mechanical defect	Bus trade	Describes situation
584	586	2	Control	31		Mechanical defect	Bus trade	Instructs supervisor to instruct operator to trade busses
586	589	3	31	Control		Mechanical defect	Bus trade	10-4
589	592	3	32	33				Asks to switch to alternate radio channel
592	598	6	33	32				10-4