Theory of Human Intervention and Design of Human-Computer Interfaces in Supervisory Control: Application to Traffic Incident Management

by

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Abstract

Of the generic human operator's roles in supervisory control, intervention into the automatic control or decision making is often regarded as a temporary compromise for a bad automatic system. It is common practice to design automatic systems to avoid human intervention as much as possible. However, for tasks of any complexity it is practically impossible to build a system with current technology, in which some human intervention is not necessary, and furthermore, in some tasks, the performance of the human operator is far better than that of a computer. Therefore supervisory control systems should be designed so that the operator can easily intervene when necessary, but at the same time such intervention must not cause the system performance to worsen.

A prescriptive model of human intervention is developed based on given probabilistic descriptions about the performance of a decision aid and the performance of an operator, and cost functions for consequences of each decision. The model is applied to traffic incident management of the Boston Central Artery/Tunnel Project, where an operator has to make a decision with given uncertain information under time pressure: (1) to dispatch agents immediately, (2) not to dispatch agents and quit, or (3) to look for further confirming or disconfirming information and decide later. The model guides an operator when to intervene and how to override the decision aid with the operator's observation.

The model provides a conceptual basis for a new human-computer interface to give operators more refined advice for alternative actions than is given in the current interface. In contrast to the current interface, which emphasizes the states of an incident which themselves are uncertain, the new interface suggests to operators an action along with a degree of certainty. Through human-in-the-loop experiments with an incident management simulator, the new interface is shown not only to eliminate unnecessary human interventions but also to guarantee correct human interventions, which results in the improvement of overall performance of incident management compared to performance with the current interface. Also the new interface reduces the operator's decision making time.

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The fear of the LORD is the beginning of wisdom;
all who follow his precepts have good understanding.
To him belongs eternal praise.
(NIV, Psalm 111:10)

List of Abbreviations

APID	All Purpose Incident Detection
BFD	Boston Fire Department
BOS	Blank Out Sign
CA/T	Central Artery/Tunnel
CO	Carbon Monoxide
CRT	Cathode Ray Tube
EMS	Emergency Medical Services
ERT	Emergency Response Team
GUI	Graphic User Interface
HAR	Highway Advisory Radio
HCI	Human-Computer Interface
IPCS	Integrated Project Control Systems
LUS	Lane Use Sign
MIMO	Multiple Input Multiple Output
MPH	Miles per Hour
MSP	Massachusetts State Police
OCC	Operations Control Center
SISO	Single Input Single Output
VMS	Variable Message Sign
VPH	Vehicles per Hour
VSLS	Variable Speed Limit Sign

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Chapter 1

Introduction

1.1 Motivation: Human Intervention in Automation

During the last decade, computer technology has advanced and has become widely available to industry. As the computer has become embedded in various machines and the machines have become automated, the role of the human operator has changed from that of direct controller to that of supervisor. Of the five supervisory roles, namely planning the task, teaching the computer, monitoring the automatic action, intervening in the automatic operation as necessary, and learning from experience, it is the intervention role which currently seems to be most lacking in theoretical or design discipline [44].

Reasons for this, the author believes, are that (i) supervisory control is commonly regarded as an intermediate phase toward automatic control from manual control, therefore it will be phased out in the near future, and (ii) in many real applications human intervention into automatic decision and/or automatic control is regarded as a temporary compromise for a bad automatic system It is common practice to design automatic systems to avoid human intervention as much as possible, and to regard such systems as less good if they call for any significant degree of human intervention. In in some ideal sense, that may be true, and we may strive to build such a fully automatic system. For tasks of any complexity, however, it is very questionable whether we can build such a real automatic system with the current technology, one in which some human intervention is never necessary. Furthermore, in some tasks, a human operator outperforms an automatic system, for example, to interpret complex visual images.

Therefore an automatic system needs to be designed so that an operator can easily and correctly intervene when necessary, but at the same time such intervention must not become the cause of destabilizing transients or otherwise make system performance worse. This issue is quite self-evident and important in a complex system like the Central Artery/Tunnel project described in the following section.

1.2 Example: Central Artery/Tunnel Project

The Central Artery/Tunnel (CA/T) project in Boston is an eleven billion dollar project involving about 120 lane-miles of tunnel and two major interstate highways through Boston. Included in the project is an elaborate traffic incident analysis and a decision support system built into a central traffic control center called the Operations Control Center (OCC). In this system, once an *incident*[1] occurs, the incident is *managed* interactively by a human operator and a decision aid in the OCC. They are augmented by sensors (several hundred video monitors, as well as optical and electromagnetic sensors) and a communication network (to further interrogate sensors and equipment beyond what is detected and communicated automatically, to dispatch tow trucks, ambulances, fire fighters, police, or repair crews, to regulate traffic by means of variable message signs and lights, and to modify flow and direction of tunnel ventilation air, etc.).

When a traffic incident occurs, an incident detection system will detect and generate an alarm to an operator. Upon accepting an alarm, the operator is given a response plan suggested by a computerized decision aid based on predefined rules and measurements through various sensors. At the moment of decision, an operator has three decision options, namely, (i) to follow the suggestion made by a decision aid, (ii) to modify it by his/her own experiences and intuition without searching for more information, or (iii) to search additional information and decide later based on the additional information. If either the decision aid were always correct and perfect, or the searching were done instantaneously and its result would be always correct, the human-computer interaction in the incident management would be simple and easy: to follow always the suggestion of the decision aid or not to use the decision aid and make his/her own response plan by searching for more information. However, the current incident management is between these extremes. The decision aid is not perfect, but performs well. The searching cannot be done instantaneously and the operator's observation cannot be fully correct. Here, how to use the suggestion of the decision aid can be considered as a problem of human intervention in automation.

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[1] Here an incident is an event which hinders traffic flow, such as vehicle collision, fire, spill of fish, power outage, or excess CO buildup in tunnel.

1.3 Objectives and Outlines

The question is how to achieve the best performance with an imperfect decision aid and an imperfect human operator. This thesis seeks to understand how and when a human operator should intervene in supervisory control systems, and to improve the overall performance of human-machine systems by providing a better way for a human operator to intervene in the context of incident management.

Chapter 2 discusses the Central Artery/Tunnel project in detail and addresses human factors issues in the current design of incident management.

A paradigm and a model of intervention are presented in the context of general supervisory control in Chapter 3. A prescriptive mathematical model of human intervention is developed based on given probabilistic data of the performance of a decision aid and the performance of an operator, and the costs of the consequence of decisions. The model provides an optimal intervention decision to an operator when and how an operator should intervene with uncertain information and under time pressure.

Chapter 4 discusses considerations of designing human-computer interfaces. After reviewing the current design of human-computer interface for the incident management of the CA/T project, a new human-computer interface is proposed based on the human intervention model.

In Chapter 5, the effectiveness of the new human-computer interface in making a response plan under time pressure is verified through human-in-the-loop experiments with the incident management simulator described in Appendix A. During experiments, the behavior of intervention, the performance, and the decision making time are measured. Conclusions and contributions of this work and suggestions for further research are listed in Chapter 6.

Decision analysis and optimization are briefly reviewed in Appendix B and Appendix C. All individual data from the human-in-the-loop experiments are listed in Appendix G.

Chapter 2

Central Artery/Tunnel Project in Boston

2.1 Overview

The Central Artery/Tunnel (CA/T) project is a 7.5 mile interstate highway project (approximately half of which is underground) that provides for the replacement of the elevated Central Artery (highway I-93) and for the extension of the Massachusetts Turnpike (highway I-90) which includes the Ted Williams Tunnel (called previously as Third Harbor Tunnel) connecting South Boston and the Logan airport (see Figure 2-1). When completed in the year 2010, the project is projected to increase the traffic volume up to 244,000 vehicles per day on the Central Artery and 97,000 vehicles per day on the Ted Williams Tunnel. It will help to reduce auto emission from idling vehicles in East Boston and the travel time through the Boston downtown [49].

In order to keep the traffic flow smooth and to clear any traffic incident in the tunnel, a central traffic management center (Operations Control Center or OCC) is being built along with sensors, traffic control devices, and emergency response teams [49, 50, 51, 52, 53].

Compared to other traffic incident management systems [3, 26, 32, 39, 55], incident management for the CA/T project is very time-critical and highly automated. When a full stream of traffic is trapped inside the tunnel by an incident, the carbon monoxide (CO) gas may build up and eventually endanger the health of trapped drivers if the incident is not cleared within a certain amount of time (current estimation is fifteen minutes according to [6]). On the other hand, since the project is the major highway connecting Boston downtown, the airport, and suburbs, operators cannot execute the *strongest* response plan for every incident: to dispatch all agencies and to close the tunnel to further

Figure 2-1: Central Artery/Tunnel Project

Table 2.1: Projected Traffic Volume without the CA/T Project

	1996	2010
Central Artery	205,000	217,000
Summer/Callahan	98,000	102,000
Tobin Bridge	93,000	102,000

Table 2.2: Projected Traffic Volume with the CA/T Project

	1996	2010
Central Artery	205,000	244,000
Ted Williams Tunnel	17,000	97,000
Summer/Callahan	97,000	72,000
Tobin Bridge	86,000	98,000

traffic. Further, some emergency response resources must be reserved to cope with any possible occurrence of additional incidents. A highly automated Integrated Project Control System (IPCS) is being built at the Operations Control Center (OCC), in order to detect incidents, quickly formulate the best response plan, and clear the incident as safely and efficiently as possible.

2.2 Incident Management

As shown in Figure 2-2, a procedure of incident management can be divided into five time intervals: detection, decision-making, dispatching, clearance, and recovery.

The detection period is from the moment when an incident occurs to the moment when an alarm is generated by the IPCS. The decision-making period is from the moment when an alarm is shown to the moment when a response plan is executed. The dispatching period is from the moment when a response plan is executed to the moment when an agent arrives at the incident location. The clearance period is from the moment when an agent arrives at the location to the moment when the incident is cleared. The recovery period is from the moment when the incident is cleared to the moment when the traffic flow returns to normal.

The task allocated for each time period is different and a human operator does not have full

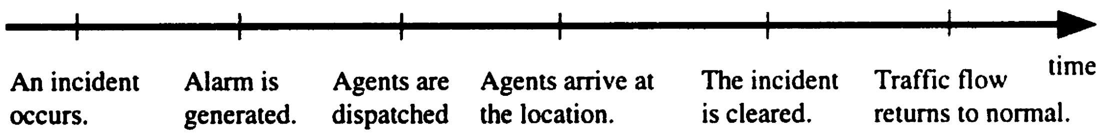

Figure 2-2: Time Flow of the CA/T Incident Management

responsibility for all time periods. During the detection period, the IPCS is supposed to detect an incident with the help of APID (All Purpose Incident Detection) algorithm [49]. Though a human operator can manually detect an incident, it is not be desirable to rely upon a human operator to monitor the whole CA/T, which is a 120 lane-mile highway. During the dispatching period, it is up to an individual agent how fast and quickly to arrive at the incident location. Once an agent, except for an emergency response team (ERT), arrives at the incident location, the arrived agent has the juridical authority over an operator at the OCC. During the clearance and recovery period, an operator simply monitors the incident and responds to what the agent asks to be done.

Therefore the most important moment of incident management for an operator is the decision-making period. During the decision-making period, an operator has to collect information about an incident, to classify the incident, to make a response plan, and to execute the response plan.

2.3 Task Analysis for Human Operator

On the basis of a CA/T design document [49, 50, 51, 52, 53], the task analysis [15, 17, 27] shows that there are five major task categories for incident management: to monitor the CA/T facilities as well as the traffic, to detect any abnormal events, to classify the detected event, to make a response plan for the event if it is an incident, and to clear the incident in time.

During the decision-making period, a human operator and the IPCS manage an incident interactively as shown in Figure 2-3. When the IPCS generates an alarm, an operator acknowledges it. Once the operator acknowledges the alarm, the IPCS gives information about the characteristics of the incident, along with a response plan. The operator evaluates the information and the response plan, and decides either to accept the suggested response plan or to search for more information. Then the operator executes the response plan with or without modification. The IPCS carries out the response plan and the operator further observes the incident and modifies the plan if necessary. In other words, the tasks of the operator are:

1. to find out whether an alarm is true or false,
2. if there is an incident, to classify what kind of incident it is by accepting the IPCS report or by looking at various displays such as video monitors, traffic maps, fire detectors, and etc.,
3. to make a response plan by accepting the plan suggested by the IPCS or by modifying it partially or fully, and
4. to execute the plan and monitor the incident.

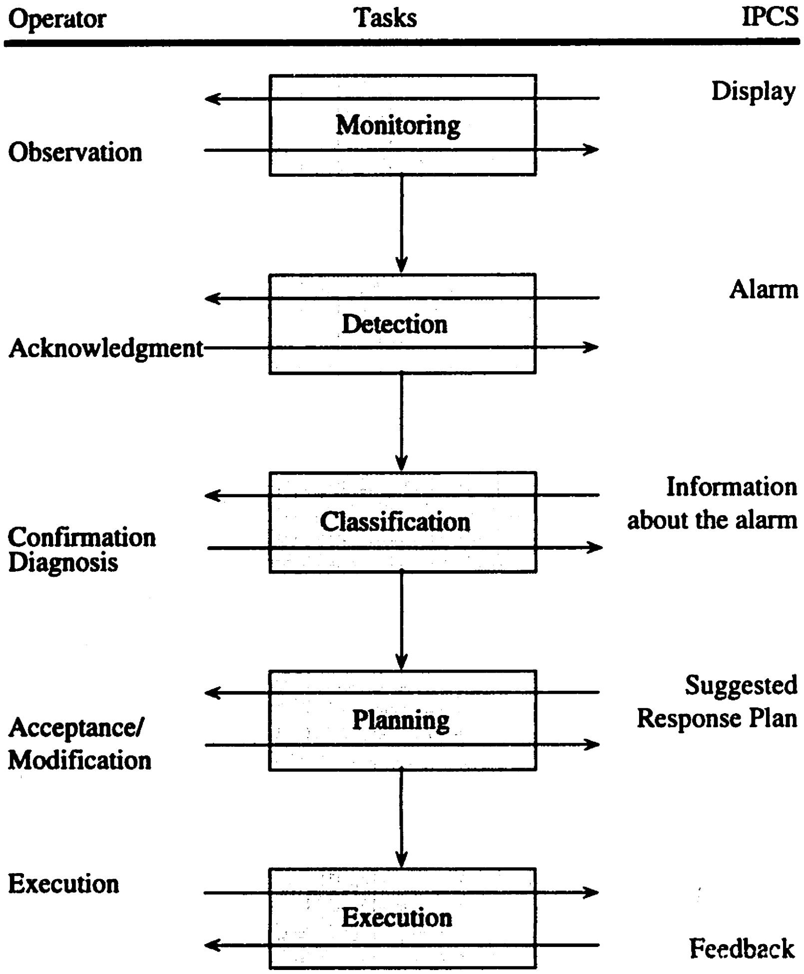

Figure 2-3: Tasks of Human Operator in the CA/T Project

2.4 Intervention: Decision Making under Time Pressure and Uncertainties

A part of the incident management procedure from the current CA/T document [49] is shown in Figure 2-4 and 2-5. Initially information about the characteristics of an incident and a response plan for the incident are provided by the IPCS. An operator collects additional information if necessary, and accepts or modifies the given response plan about the incident location, the incident type, the blockage pattern, the possibility of an injured person, the possibility of fire, and the possibility of hazardous material spillage. Since the information provided by the IPCS is not guaranteed to be perfect, an operator may spend time on collecting additional information. It is expected that the more time spent, the better information can be collected, and the better information results in a better response plan. However an operator cannot spend too much time on getting information, because the incident can get worse as time goes on, and there are environmental regulations regarding CO buildup, etc. The questions for an operator are:

1. how should/does an operator evaluate the information given by the IPCS?
2. how long should/does an operator collect information about an incident?
3. why/when should/does an operator modify a response plan given by the IPCS?

As discussed earlier, an operator's behavior to override an automatic system can be considered as an intervention. These questions should be answered in the framework of human intervention in supervisory control.

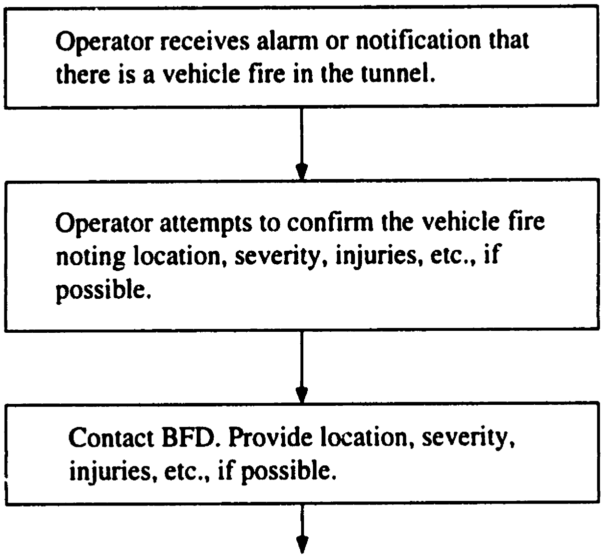

Figure 2-4: Incident Management Procedure for Fire. BFD is Boston Fire Department.

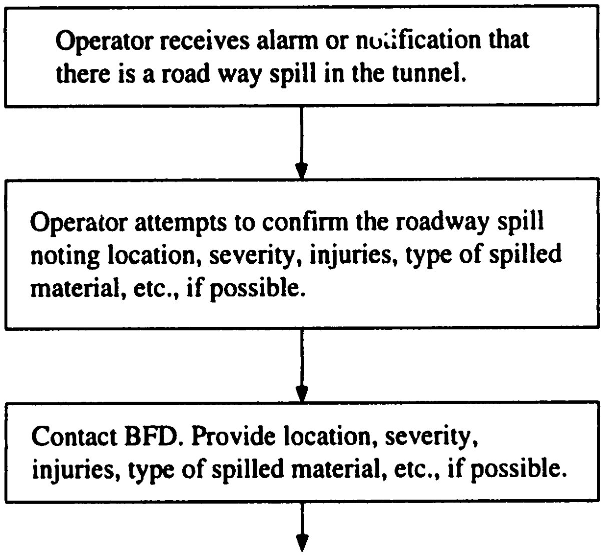

Figure 2-5: Incident Management Procedure for Spill

Chapter 3

Theory of Human Intervention

3.1 Supervisory Control

3.1.1 Automation in Decision Making and Control

Decision making is information processing. It is a process by which people search alternative actions, evaluate the consequence of each action, and select a course of action. Control is the execution of a course of action and usually means closed-loop control which involves generating a new control input to the system by comparing the measurements of current outputs from it to given desired outputs. Control is a more or less continuous action to maintain or improve the performance in spite of disturbances. On the other hand, a decision is made at discrete instances of time in order to set a task goal.

Automation can be achieved and categorized in various levels of decision making and control depending on who or what controls, how it is controlled, and who or what makes a decision. There are four known methodologies, namely, manual control, automatic control, human[1] supervisory control, and autonomous control.

Manual control is a way to control a system by which a person receives continuously through his or her senses information about states of a given system and manipulates continuously mechanical or electrical devices in order to minimize error or to maximize performance, whatever is appropriate [37].

Automatic control is a way to control a system involving machines or computers only with predefined desired outputs. An automatic controller measures the current states of a given system

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[1] In this thesis the adjective term *human* is dropped in subsequent text unless necessary.

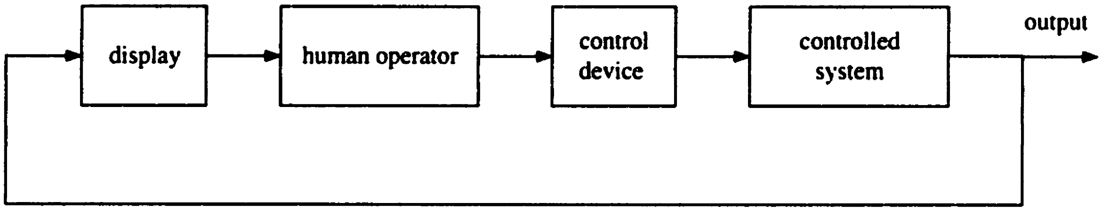

Figure 3-1: Manual Control

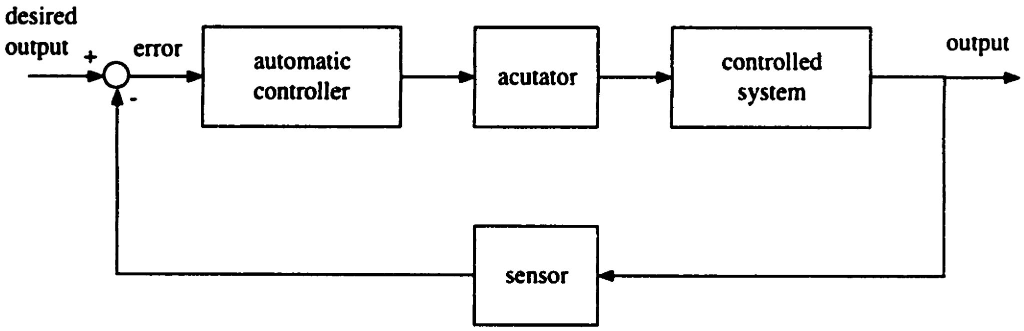

Figure 3-2: Automatic Control

and generates a control input in the direction of reducing the difference in desired outputs and expected outputs [10].

Supervisory control is that a human operator is intermittently giving a command and receiving information from a computer that itself is an automatic controller to a given system [44].

Autonomous control is that a computer itself plans and generates desired outputs, and makes a control law based on the desired outputs and the current outputs.

In this research, we consider a supervisory control system which consists of a decision aid and an automatic controller (one which can execute a decision and bring system performance to some desired state, or in any case one whose expected action can be anticipated relative to the advice of the decision aid).

3.1.2 Operator's Roles in Supervisory Control

Sheridan [44] lists five human operator's roles in supervisory control: planning, teaching, monitoring, intervening, and learning. Planning involves understanding of the controlled system, setting goals and objectives, and making a course of actions to achieve the goals. An operator teaches, programs, or commands an automatic controller through a control device such as a keyboard, a mouse, or a joystick. Once an automatic controller and a controlled system are running, it is an important role of an operator to monitor and detect any discrepancy at the current time or any projected discrepancy in the near future between desired outputs and real outputs. When the current or the expected performance of the controlled system is not acceptable, an operator has to intervene in order to give a new command to the automatic controller or to take control over the automatic controller. After each execution, the operator keeps the history and analyzes abnormalities to update or tune the automatic controller or to refine his or her goals and commands.

3.2 Intervention

3.2.1 Definition

A supervisory control system has many different control tasks and modes, in order to carry out the variety of tasks imposed. Seldom is the full set of criteria for the change of control task or mode available or preprogrammed, though some "if...then" may be preprogrammed in a decision aid or an automatic controller. As task demands change, there are needs to change back and forth among different control tasks and control modes. The decision activity therefore requires a human operator, and is called intervention.

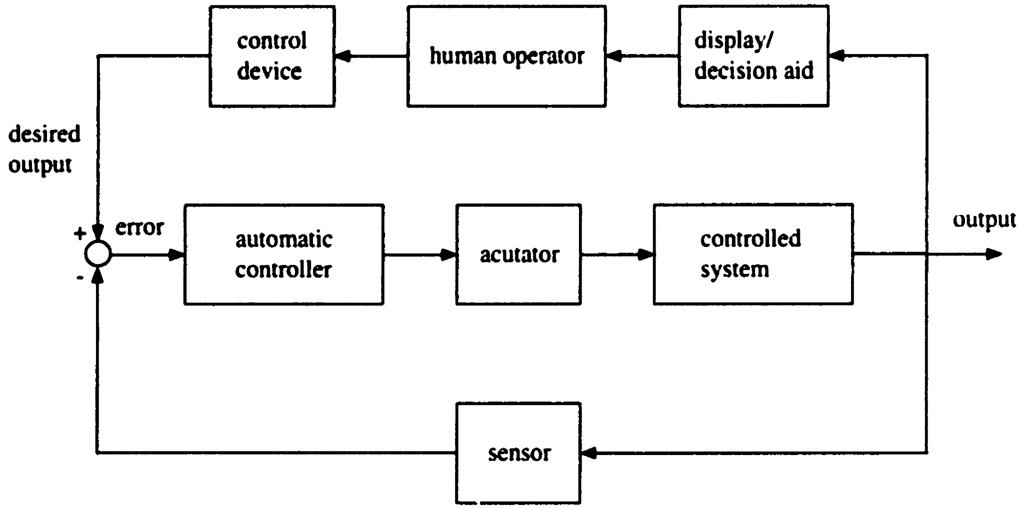

Figure 3-3: Supervisory Control

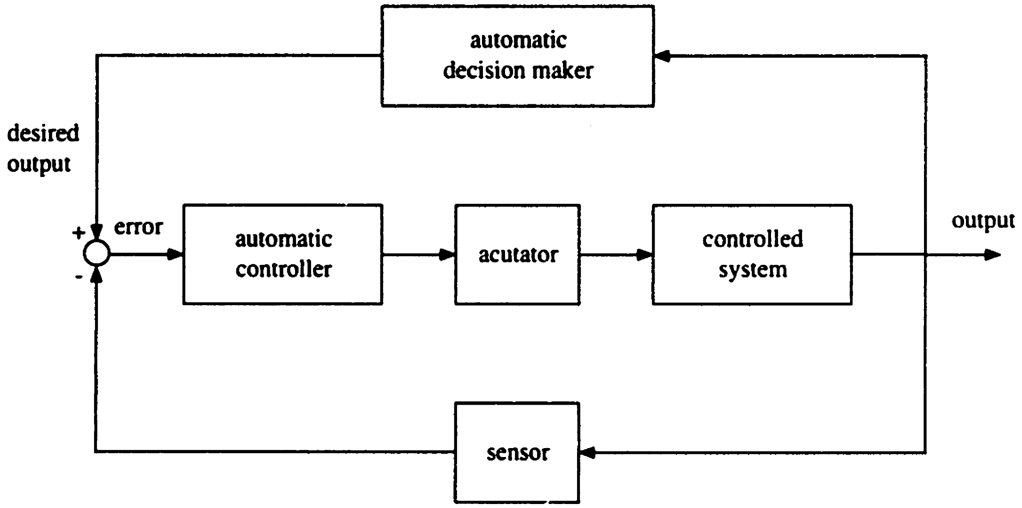

Figure 3-4: Autonomous Control

Human intervention in supervisory control is an operator's action to supplement ongoing automatic control activities, to take over control entirely after the desired goal state is reached, or to interrupt the automatic control in emergencies to specify a new command. Intervention implies changes in the control goal, the control objectives, the structure of the automatic controller, or the parameters of the automatic controller as the environment or the controlled system is changed.

An intervention can also be described as a human operator's action to modify or to reject a decision generated by a decision aid, or to stop an ongoing automatic control activity, to adjust some control parameters, to initiate another automatic control task, or to take over the automatic control and do a control task manually.

3.2.2 Paradigm of Intervention

It is proposed to consider four types of intervention as shown in Figure 3-5 associated with a decision aid and an automatic controller in a supervisory control system.

Suppose an abnormal situation occurs and an operator is notified. The operator can employ a decision aid for its advice; or make his or her own decision (Type I intervention) based on his or her knowledge and experience. If the decision aid is employed but the operator does not wish to implement its resulting decision (or automatic action considering the advice received), he or she then can modify the advice partially or fully (Type II intervention). With the decision (whether the decision was made by the computer or the operator), the operator may initiate automatic control; or he or she may decide to go directly to manual control (Type III intervention). In the middle of or at the end of the automatic control the operator may feel that manual control takeover is necessary, and may then control the process manually (Type IV intervention).

Type I intervention and Type II intervention are related to decision making, and Type III intervention and Type IV intervention to control. Type I intervention happens before a computer generates a decision. Type II intervention occurs after a computer suggests a decision. Type III intervention happens before initiating automatic control and Type IV intervention is in the middle of or at the end of automatic control.

3.3 Modeling of Human Intervention

3.3.1 Literature Review

Though intervention is an important role of an operator in supervisory control, its theory has not been well developed. Recently some models of intervention have been developed.

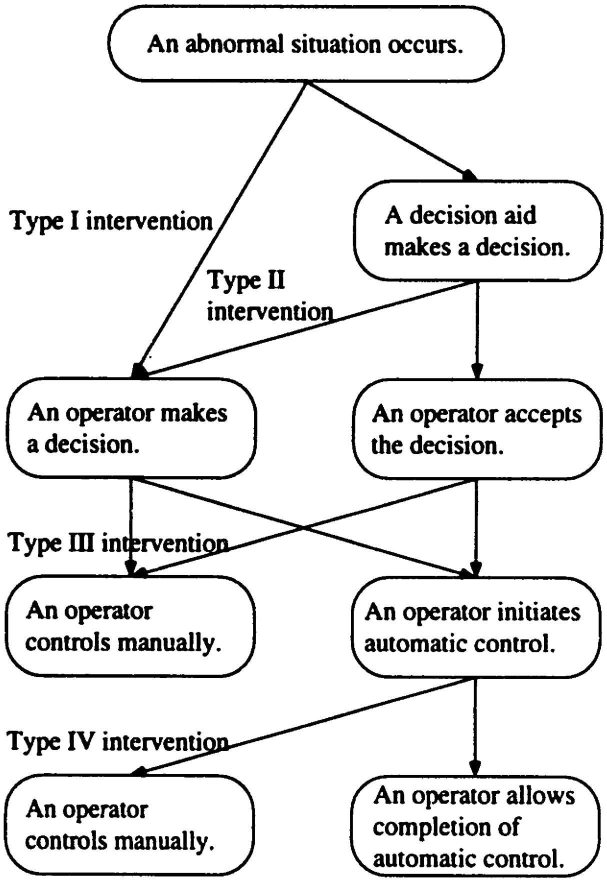

Figure 3-5: Paradigm of Intervention

Muir [30, 31] extended psychological models of trust between humans to human-machine or human-computer systems in order to guide how to design decision aids and calibrate users' trust in decision aids. She provided a qualitative variable, *trust*, as a first step in describing human intervention in supervisory control, but she did not show any conclusive links between the human-machine trust and the performance of a human-machine system.

Lee and Moray [21, 22] simulated a semi-automatic pasteurization plant. They conducted experiments with human subjects on how an operator switched from an automatic control mode to a manual control mode or vice versa, when one component of the pasteurization plant failed. During 36 trials over two days, a subject faced consecutive failures in the last 12 trials and was asked to rate his or her trust in the automation and self-confidence. They concluded that automation was used when trust exceeds self-confidence; manual control was used when the opposite was true. However, trust and self-confidence were measured subjectively, and there was no objective way to build a human-machine system to ensure trust and self-confidence correctly reflected. Furthermore, because they set up failures in the last 12 trials while there was no failure in the first 24 trials, experimental subjects were forced by surprise to build a bias. The resulting subjective ratings could be biased. It cannot explain human intervention in a steady state operation of supervisory control.

Kirlik [18] showed how and when an experimental subject employed an autopilot in a light helicopter simulator. When a decision aid could be selectively engaged by a subject, such a decision aid eliminated some task demands but created new ones associated with with engaging, programming, and disengaging of the decision aid. There was a possibility that the costs associated with engaging, programming, and disengaging a decision aid outweighed the benefits of using the decision aid. For various costs of using the autopilot, a sensitivity analysis based on a Markov decision model was done in order to describe when a subject used the autopilot. It was shown that experimental subjects managed the autopilot system to keep workload and performance at acceptable levels. His results cannot explain human intervention for a supervisory control system the decision aid of which is imperfect, which nevertheless generates a suggestion and displays it automatically. According to his results, an operator should use the decision aid always, because the associated costs with engaging, programming, and disengaging are zero. But since the decision aid is imperfect, an operator should not use the decision aid always.

Riley [38] presented factors which influenced human use of automation through a series of experiments. He claimed that the reliance depends on risk, self-confidence, task complexity, trust in automation, fatigue, and machine accuracy.

By and large, these experimental efforts focused on a set of subjective estimations of variables such as workload, trust, self-confidence, or task complexity. Their models are inherently subjective and descriptive[2]. Since human decision makers are inherently biased and suboptimal [13], it is argued that a descriptive model of human intervention based on the subjective ratings does not say how to achieve the optimal performance in any particular human-machine system.

It is important to understand human intervention as a problem of decision making and to model human intervention in the framework of decision analysis for the purpose of optimizing the performance of a human-machine system. In the following sections, a prescriptive model of human intervention will be developed, relative to use of a less-than-perfect decision aid.

3.3.2 Review of Decision Analysis

A decision analysis says how rational people should make decisions based on the probability of events and the preferences for the corresponding consequences of the possible events (e.g., see [7, 8]). Probabilities express the knowledge of the true states of the system and can be either objective or subjective, depending on how they are measured. Also a decision maker determines his or her preferences or *utilities* objectively or subjectively. They express the value for each decision-state pair. The most common decision criterion is to maximize the expected utility among all the decisions (or to minimize the expected negative utility).

Suppose the state x is one of $\{X_1, \ldots, X_n\}$. Let $p(x = X_i)$ denote the probability that the state x is X_i, and u_{ji} is the utility for the decision $d = D_j$ when $x = X_i$. A decision d^* which maximizes the expected utility is

$$d^* = \arg\max_j \sum_{i=1}^{n} u_{ji} p(x = X_i) \quad . \tag{3.1}$$

It is worthwhile to note that good decision making does not guarantee a good decision result from every decision made. In the long run, however, if decisions are made consistently based on the rational criteria, it guarantees that good results will occur more frequently than bad ones. More detailed review of decision analysis can be found in Appendix B.

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[2] A prescriptive model is how rational people should make a decision and a descriptive model is how people actually make a decision. Some authors distinguish a prescriptive model from a *normative* model by emphasizing that a prescriptive model takes into account how people evaluate and integrate information and prescribes decisions on this ground, while a normative model is a mathematical formalizations without considering human characteristics [24].

3.3.3 Human Intervention in Single-Input Single-Output Supervisory Control Systems

Problem

Let us consider a simplified version of incident management such that an operator has to decide whether or not to dispatch an agent, for example, an emergency medical service (EMS) based on the information given by a decision aid about the existence of an injured person. When a decision aid detects and notices that there is an injured person, the operator has three choices (1) to accept the suggestion and dispatch an EMS, (2) to reject it and quit, or (3) to search additional information and make a decision based on the additional information. After searching additional information, the operator has two decisions: (1) to dispatch an EMS, or (2) not to dispatch an EMS. The question here is whether to accept the suggestion of the decision aid, and how to override the suggestion after searching additional information if appropriate.

Notations

Let x denote the state of an injured person which can be that there is an injured person or not, i.e., X_1 = there is an injured person or X_2 = there is no injured persion. The decision d is one of D_1 = dispatch an EMS, D_2 = do not dispatch an EMS, and D_3 = search. Also let y represent the measurement of a decision aid and z represent the observation of an operator. Assume that y and z are independent because the sensors that an operator uses and the sensors that a decision aid uses are different and independent.

Data

When a decision aid detects an injury, the detection can be wrong. The performance of the decision aid can be described in terms of conditional probabilities of a measurement y given a state x as follows:

$$\begin{aligned}
p(y = X_1 \mid x = X_1) &= p_{11} \\
p(y = X_2 \mid x = X_1) &= p_{21} = 1 - p_{11} \\
p(y = X_1 \mid x = X_2) &= p_{12} = 1 - p_{22} \\
p(y = X_2 \mid x = X_2) &= p_{22} \qquad (3.2)
\end{aligned}$$

By the same way, the performance of an operator to search information correctly can expressed as conditional probabilities of an observation z given a state x.

$$\begin{aligned}
&p(z = X_1 \mid x = X_1) = q_{11} \\
&p(z = X_2 \mid x = X_1) = q_{21} = 1 - q_{11} \\
&p(z = X_1 \mid x = X_2) = q_{12} = 1 - q_{22} \\
&p(z = X_2 \mid x = X_2) = q_{22}
\end{aligned} \tag{3.3}$$

Note that before an incident occurs, p_{ij}'s and q_{ij}'s can be predetermined by histories of performance, tests, or training. We assume that $q_{11} + q_{22} > 1$ without loss of generality; otherwise an operator is very poor at the observations.

When an operator makes a response plan for an incident, from the viewpoint of an operator, the incident has already occurred and there is a minimum time needed to clear the incident. Therefore the costs of dispatching and not dispatching can be considered as the costs of errors, say, dispatching an EMS when one should not, or not dispatching an EMS when one should. We take the cost of dispatching an EMS when one should be, and the cost of not dispatching an EMS when one should not be to be zero. Also the cost of collecting additional information when an EMS should not be dispatched can be considered the cost of time consumed for searching information by an operator. The cost of collecting additional information when an EMS should be dispatched can be the sum of the cost of time consumed for searching information and of the clearing time difference between when it is dispatched immediately and when it is dispatched after search. The costs of each decision associated with each state can then be summarized in matrix form as shown in Table 3.1. For the convenience of the computation, let $c_{31} = c_{32} + c_3$.

Approach

The problem here is to find the optimal decision when the decision aid gives the characteristics of an incident. This problem can be considered as an optimization problem to minimize the expected cost. It can be solved by using the dynamic programming method (Appendix C).

Table 3.1: Costs of Consequences of Decisions

	INJURY ($x = X_1$)	NO INJURY ($x = X_2$)
DISPATCH ($d = D_1$)	0	c_{12}
NOT DISPATCH ($d = D_2$)	c_{21}	0
SEARCH ($d = D_3$)	c_{31}	c_{32}

Let time t_1 be the time when the decision aid provides to the operator the characteristics of an incident, and t_2 be the time when the search is done, if the operator decides to search. At each time step, a decision must be made. Let d_1 and d_2 be the decisions made at time step t_1, and t_2, respectively. d_1 can be one of $\{D_1, D_2, D_3\}$. d_2 can be one of $\{D_1, D_2\}$, because the available decisions are to dispatch or not to dispatch, after the searching is done. Note that if d_1 is either D_1 or D_2, then there does not exist d_2.

The decision criterion is to select a decision which minimizes the expected cost at each time. Let J_1 and J_2 be the cost functions at time t_1 and t_2, respectively. Let J_1^* and J_2^* be the minimum for J_1 and J_2, respectively, and d_1^* and d_2^* be the optimal decisions which achieve the minimum costs J_1^* and J_2^*, respectively.

$$J_1^* = \min \mathrm{E}\left[\text{cost of } d_1 = D_1, \text{cost of } d_1 = D_2, \text{cost of } d_1 = D_3 + J_2^*\right] \tag{3.4}$$

$$J_2^* = \min \mathrm{E}\left[\text{cost of } d_2 = D_1, \text{cost of } d_2 = D_2\right] \tag{3.5}$$

The method to solve for J_1^* and J_2^* is exactly as same as the method in the dynamic programming: after finding probabilities considering all possible cases, first solve for J_2^*, and second for J_1^*.

Probabilities

To find the expected costs, we need to find the probability of $x = X_1$ by using the data in (3.2) and (3.3) as information is collected. The value of the probability can be changed based on the incident data, the measurement of the decision aid, and the observation of the operator. The more confirming information increases the value of the probability of an injury, and the more disconfirming information decreases it.

Let p_0 represent the probability of an injury based on the incident data without considering the measurement of the decision aid. Let p_1 be the probability of an injury after the decision aid measures it. Let p_2 denote the probability of an injury based on the measurement of the decision aid and the observation of the operator (Figure 3-6).

We can think p_0 as a priori probability of an injury for each incident, p_1 as a conditional proba-

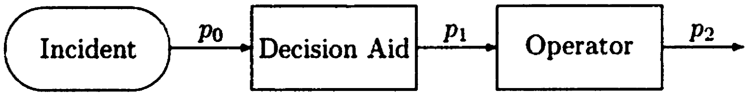


Figure 3-6: Probabilities

bility of an injury given on the measurement of the decision aid, and p_2 as a conditional probability of an injury given on the measurement of the decision and the observation of the operator.

$$p_0 = p(x = X_1) \tag{3.6}$$

$$p_1 = p(x = X_1 \mid y) \tag{3.7}$$

$$p_2 = p(x = X_1 \mid y, z) \tag{3.8}$$

By using Bayes' rule (see Appendix B), we can solve for probabilities, p_1 and p_2, in terms of p_0, p_{ij}'s, and q_{ij}'s. For p_1, we can express it as:

$$\begin{aligned} p_1 &= p(x = X_1 \mid y) \\ &= \frac{p(y \mid x = X_1) p_0}{p(y)} \end{aligned} \tag{3.9}$$

and

$$\begin{aligned} 1 - p_1 &= p(x = X_2 \mid y) \\ &= \frac{p(y \mid x = X_2)(1 - p_0)}{p(y)} \end{aligned} \tag{3.10}$$

We can solve for $p(y)$, by adding p_1 (3.9) and $1 - p_1$ (3.10), and by using the fact that the sum is one.

$$\begin{aligned} p(y) &= p(y \mid x = X_1) p_0 + p(y \mid x = X_2)(1 - p_0) \\ &= \begin{cases} p_{11} p_0 + p_{12}(1 - p_0) & \text{if } y = X_1 \\ p_{21} p_0 + p_{22}(1 - p_0) & \text{if } y = X_2 \end{cases} \end{aligned} \tag{3.11}$$

Then we can express p_1 as

$$p_1 = \begin{cases} \frac{p_{11} p_0}{p_{11} p_0 + p_{12}(1 - p_0)} & \text{if } y = X_1 \\ \frac{p_{21} p_0}{p_{21} p_0 + p_{22}(1 - p_0)} & \text{if } y = X_2 \end{cases} \tag{3.12}$$

In the same way, we can solve for the probability p_2 in terms of p_1 by using $p(x, y, z) = p(y)p(x|y)p(z|x, y)$

and the independence of y and z:

$$\begin{aligned} p_2 &= p(x = X_1 | y, z) \\ &= \begin{cases} \frac{q_{11}p_1}{q_{11}p_1 + q_{12}(1-p_1)} & \text{if } z = X_1 \\ \frac{q_{21}p_1}{q_{21}p_1 + q_{22}(1-p_1)} & \text{if } z = X_2 \end{cases} \end{aligned} \tag{3.13}$$

where

$$p(z = X_1) = q_{11}p_1 + q_{12}(1 - p_1) \tag{3.14}$$

$$p(z = X_2) = q_{21}p_1 + q_{22}(1 - p_1) \tag{3.15}$$

Minimal Costs

Before proceeding to solve for the minimal costs, it can be shown that $\frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} < \frac{c_{12}}{c_{12}+c_{21}} < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}}$ based on the assumption $q_{11} + q_{22} > 1$ (see page 56 for the proof).

As discussed earlier, J_2^* is needed to be solved first, which is expressed as:

$$\begin{aligned} J_2^*(z) &= \min\left[c_{12}(1 - p_2), c_{21}p_2\right] \\ &= \begin{cases} \min\left[\frac{c_{12}q_{12}(1-p_1)}{p(z=X_1)}, \frac{c_{21}q_{11}p_1}{p(z=X_1)}\right] & \text{if } z = X_1 \\ \min\left[\frac{c_{12}q_{22}(1-p_1)}{p(z=X_2)}, \frac{c_{21}q_{21}p_1}{p(z=X_2)}\right] & \text{if } z = X_2 \end{cases} \end{aligned} \tag{3.16}$$

The J_2^* can be expressed explicitly in terms of z and p_1.

$$J_2^* = \begin{cases} \frac{c_{12}q_{12}(1-p_1)}{p(z=X_1)} & \text{if } z = X_1 \text{ and } \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \le p_1 \le 1 \\ \frac{c_{21}q_{11}p_1}{p(z=X_1)} & \text{if } z = X_1 \text{ and } 0 \le p_1 < \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \\ \frac{c_{12}q_{22}(1-p_1)}{p(z=X_2)} & \text{if } z = X_2 \text{ and } \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \le p_1 \le 1 \\ \frac{c_{21}q_{21}p_1}{p(z=X_2)} & \text{if } z = X_2 \text{ and } 0 \le p_1 < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \end{cases} \tag{3.17}$$

By observing carefully the above expression of J_2^* with the inequality $\frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}}$, we notice that in some region of the probability p_1 the optimal decision d_2^* does not depend on the observation z. For example, if $p_1 > \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}}$, J_2^* is either $\frac{c_{12}q_{12}(1-p_1)}{p(z=X_1)}$ or $\frac{c_{12}q_{22}(1-p_1)}{p(z=X_2)}$, which is only achieved by $d_2^* = D_1$. On the other hand, if $p_1 < \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}}$, then J_2^* is either $\frac{c_{21}q_{11}p_1}{p(z=X_1)}$ or $\frac{c_{21}q_{21}p_1}{p(z=X_2)}$, which is achieved by $d_2^* = D_2$. And if $\frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} < p_1 < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}}$, the minimal cost J_2^* can be achieved by $d_2^* = D_1$ if $z = X_1$ and $d_2^* = D_2$ if $z = X_2$. The optimal decision d_2^* can be written as:

$$d_2^* = \begin{cases} D_1 & \text{if } \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \le p_1 \le 1 \\ D_i & \text{if } z = X_i \text{ and } \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \le p_1 < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \\ D_2 & \text{if } 0 \le p_1 < \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \end{cases} \tag{3.18}$$

and can be shown in Figure 3-7.

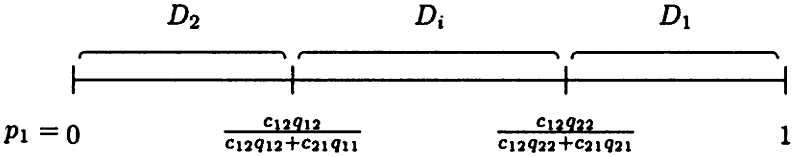


Figure 3-7: Optimal decision d_2^* after searching information

Now the minimal cost J_1^* can be solved by using J_2^*.

$$J_1^* = \min\left[c_{12}(1-p_1), c_{21}p_1, p(z=X_1)\left\{c_{31} + J_2^*(z=X_1)\right\} + p(z=X_2)\left\{c_{32} + J_2^*(z=X_2)\right\}\right] \tag{3.19}$$

since $\mathrm{E}\left[J_2^*\right] = p(z = X_1)J_2^*(z = X_1) + p(z = X_2)J_2^*(z = X_2)$. In order to find J_1^*, we need to consider all possible cases. One easy way to do this is to use the fact that $c_{12}(1-p_1) < c_{21}p_1$ if $p_1 > \frac{c_{12}}{c_{12}+c_{21}}$ and the result of J_2^* in (3.17). Then we can see

$$J_1^* = \begin{cases} \min & \left[c_{12}(1-p_1),\ c_{31}p(z=X_1) + c_{32}p(z=X_2) + c_{12}q_{12}(1-p_1) + c_{12}q_{22}(1-p_1)\right] \\ & \text{if } \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \le p_1 \le 1 \\ \min & \left[c_{12}(1-p_1),\ c_{31}p(z=X_1) + c_{32}p(z=X_2) + c_{12}q_{12}(1-p_1) + c_{21}q_{21}p_1\right] \\ & \text{if } \frac{c_{12}}{c_{12}+c_{21}} \le p_1 < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \\ \min & \left[c_{21}p_1,\ c_{31}p(z=X_1) + c_{32}p(z=X_2) + c_{12}q_{12}(1-p_1) + c_{21}q_{21}p_1\right] \\ & \text{if } \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \le p_1 < \frac{c_{12}}{c_{12}+c_{21}} \\ \min & \left[c_{21}p_1,\ c_{31}p(z=X_1) + c_{32}p(z=X_2) + c_{21}q_{11}p_1 + c_{21}q_{21}p_1\right] \\ & \text{if } 0 \le p_1 < \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \end{cases} \tag{3.20}$$

For each interval of p_1, we can find the minimum cost. For the first interval $\frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \le p_1 \le 1$, it is obvious that $c_{12}(1-p_1)$ is the minimum and D_1 is the optimal decision. For the fourth interval $0 \leq p_1 < \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}}$, it is also obvious that $c_{21}p_1$ is the minimum and D_2 is the optimal decision. For the second and the third interval, we need to check which one is the minimum. For the second interval of p_1, we can find α such that at $p_1 = \alpha$,

$$c_{12}(1-\alpha) = c_{31}(q_{11}\alpha + q_{12}(1-\alpha)) + c_{32}(q_{21}\alpha + q_{22}(1-\alpha)) + c_{12}q_{12}(1-\alpha) + c_{21}q_{21}\alpha \tag{3.21}$$

By solving the above equation for α, we have

$$\alpha = \frac{c_{12}q_{22} - c_{32} - c_3q_{12}}{c_{12}q_{22} + c_{21}q_{21} + c_3(q_{11} + q_{22} - 1)} \tag{3.22}$$

It implies that if $p_1 > \alpha$, then J_1^* is $c_{12}(1-p_1)$ (or the optimal decision d_1^* is D_1), and if $p_1 < \alpha$, then J_1^* is $c_{31}p(z = X_1) + c_{32}p(z = X_2) + c_{12}q_{12}(1-p_1) + c_{21}q_{21}p_1$ (or the optimal decision is D_3), for $\frac{c_{12}}{c_{12}+c_{21}} \leq p_1 < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}}$.

In the same way, we can find β for the third interval such that if $p_1 < \beta$, then J_1^* is $c_{21}p_1$ (or the optimal decision is D_2), and if $p_1 > \beta$, then J_1^* is $c_{31}p(z = X_1) + c_{32}p(z = X_2) + c_{12}q_{12}(1-p_1) + c_{21}q_{21}p_1$ (or the optimal decision is D_3), for $\frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \leq p_1 < \frac{c_{12}}{c_{12}+c_{21}}$. β can be expressed as:

$$\beta = \frac{c_{12}q_{12} + c_{32} + c_3q_{12}}{c_{12}q_{12} + c_{21}q_{11} - c_3(q_{11} + q_{22} - 1)} \tag{3.23}$$

Then the optimal decision d_1^* can be expressed for each interval of p_1 and shown in Figure 3-8.

$$d_1^* = \begin{cases} D_1 & \text{if } \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \leq p_1 \leq 1 \\ D_1 & \text{if } \alpha < \frac{c_{12}}{c_{12}+c_{21}} \leq p_1 < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \\ D_1 & \text{if } \frac{c_{12}}{c_{12}+c_{21}} \leq \alpha \leq p_1 < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \\ D_3 & \text{if } \frac{c_{12}}{c_{12}+c_{21}} \leq p_1 < \alpha < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}} \\ D_3 & \text{if } \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \leq \beta \leq p_1 < \frac{c_{12}}{c_{12}+c_{21}} \\ D_2 & \text{if } \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \leq p_1 < \beta < \frac{c_{12}}{c_{12}+c_{21}} \\ D_2 & \text{if } \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \leq p_1 < \frac{c_{12}}{c_{12}+c_{21}} < \beta \\ D_2 & \text{if } 0 \leq p_1 < \frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} \end{cases} \tag{3.24}$$

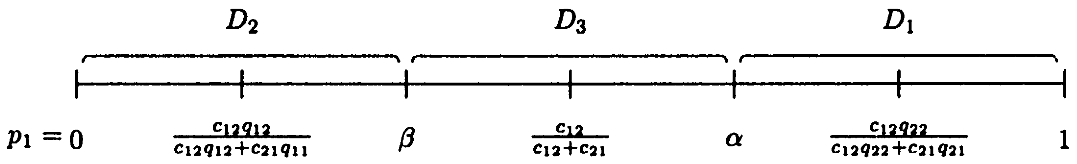


Figure 3-8: Optimal decision d_1^* before searching information

Summary: The Rule of Intervention

The rule of intervention can be summarized as follows: If the operator's performance is relatively good ($q_{11} + q_{22} > 1$), and the costs of searching additional information ($c_{31} = c_{32} + c_3$ and c_{32}) are small compared to the costs of incorrect dispatching or not dispatching decisions (c_{12} and c_{21}) such that

$$c_{32} + c_3 \frac{c_{12}q_{11} + c_{21}q_{12}}{c_{12} + c_{21}} < (q_{11} + q_{22} - 1)\frac{c_{12}c_{21}}{c_{12} + c_{21}} \tag{3.25}$$

$$c_{32} + c_3 \frac{c_{12}(2q_{12} - q_{11}) + c_{21}q_{12}}{c_{12} + c_{21}} < (q_{11} + q_{22} - 1)\frac{c_{12}c_{21}}{c_{12} + c_{21}} \tag{3.26}$$

then there exist α and β such that

$$\frac{c_{12}q_{12}}{c_{12}q_{12} + c_{21}q_{11}} < \beta < \frac{c_{12}}{c_{12} + c_{21}} < \alpha < \frac{c_{12}q_{22}}{c_{12}q_{22} + c_{21}q_{21}} \tag{3.27}$$

where

$$\alpha = \frac{c_{12}q_{22} - c_{32} - c_3q_{12}}{c_{12}q_{22} + c_{21}q_{21} + c_3(q_{11} + q_{22} - 1)} \tag{3.28}$$

$$\beta = \frac{c_{12}q_{12} + c_{32} + c_3q_{12}}{c_{21}q_{11} + c_{12}q_{12} - c_3(q_{11} + q_{22} - 1)} \tag{3.29}$$

and the rule of intervention for an operator is

$$d^* = \begin{cases} \text{intervene and follow your observation} & \text{if } \beta \le p_1 \le \alpha \\ \text{do not intervene, and follow the decision aid} & \text{otherwise} \end{cases} \tag{3.30}$$

If the inequality (3.25) is not satisfied and the inequality (3.26) is satisfied, then it means that $\alpha < \frac{c_{12}}{c_{12}+c_{21}}$. By the way, it can be easily shown that if the inequality (3.26) is satisfied then the inequality (3.25) is always satisfied. Therefore the optimal intervention decision is

$$d^* = \begin{cases} \text{intervene and follow your observation} & \text{if } \beta \le p_1 \le \frac{c_{12}}{c_{12}+c_{21}} \\ \text{do not intervene, and follow the decision aid} & \text{otherwise} \end{cases} \tag{3.31}$$

If either inequality (3.25) or the inequality (3.26) is not satisfied, then $\alpha < \frac{c_{12}}{c_{12}+c_{21}}$ and $\beta > \frac{c_{12}}{c_{12}+c_{21}}$. Therefore

$$d^* = \text{do not intervene, and follow the decision aid} \tag{3.32}$$

3.3.4 Human Intervention in Multiple-Input Multiple-Output Supervisory Control

Consider a multiple-input multiple-output supervisory control system. There are many independent decisions for an operator to make at the same time. For the incident management of the CA/T project, the decision aid suggests four decisions at the same time whether to dispatch an emergency response team, to dispatch the Massachusetts State Police, to dispatch the Boston Fire Department, or to dispatch an emergency medical service. An operator must then decide whether to accept the advice given by the decision aid, and then which information to search first among the information to be sought.

The operator's decisions can be made independently by following the rule of intervention developed in the previous section, because they are assumed independent. The only question left is which information to search first among the various decisions. The criterion used for the optimal selection is to choose the information first which maximizes the expected gain.

Let ΔJ be the expected gain for searching information related to a decision. Let D_1 and D_2 be to dispatch the corresponding agent, and not to dispatch the corresponding agent, respectively. Then before searching the corresponding information, the expected gain by searching is expressed as:

$$\begin{aligned} \Delta J^* &= \min \mathrm{E}\left[\text{cost of } D_1 \text{ before searching}, \text{cost of } D_2 \text{ before searching}\right] \\ &\quad - \min \mathrm{E}\left[\text{cost of } D_1 \text{ after searching}, \text{cost of } D_2 \text{ after searching}\right] \end{aligned} \tag{3.33}$$

The maximum gain ΔJ^* can be sought by using (3.17) and (3.20).

$$\Delta J^* = \begin{cases} c_{12}(1-p_1) - c_{31}\left[q_{11}p_1 + q_{12}(1-p_1)\right] - c_{32}\left[q_{21}p_1 + q_{22}(1-p_1)\right] & \\ -c_{12}q_{12}(1-p_1) - c_{21}q_{21}p_1 & \text{if } \frac{c_{12}}{c_{12}+c_{21}} < p_1 < \alpha \\ c_{21}p_1 - c_{31}\left[q_{11}p_1 + q_{12}(1-p_1)\right] - c_{32}\left[q_{21}p_1 + q_{22}(1-p_1)\right] & \\ -c_{12}q_{12}(1-p_1) - c_{21}q_{21}p_1 & \text{if } \beta < p_1 < \frac{c_{12}}{c_{12}+c_{21}} \end{cases} \tag{3.34}$$

The above expressions can be simplified by introducing a new variable Δp_1

$$\Delta p_1 = \begin{cases} \alpha - p_1 & \text{if } \frac{c_{12}}{c_{12}+c_{21}} < p_1 < \alpha \\ p_1 - \beta & \text{if } \beta < p_1 < \frac{c_{12}}{c_{12}+c_{21}} \end{cases} \tag{3.35}$$

Then

$$\Delta J^* = \begin{cases} \left[c_{12}q_{22} + c_{21}q_{21} + c_3(q_{11}+q_{22}-1)\right]\Delta p_1 & \text{if } \frac{c_{12}}{c_{12}+c_{21}} < p_1 < \alpha \\ \left[c_{12}q_{22} + c_{21}q_{21} - c_3(q_{11}+q_{22}-1)\right]\Delta p_1 & \text{if } \beta < p_1 < \frac{c_{12}}{c_{12}+c_{21}} \end{cases} \tag{3.36}$$

If an operator has many searching decisions, the operator must search for an information, ΔJ^* of which is the largest first in (3.36).

3.3.5 Human Intervention in SISO Supervisory Control: Time-Varying Cases

In this section, let us consider that the costs and the performance of human operator are time-varying. Suppose the searching costs (c_{31}, c_{32}) and the probabilities (q_{11}, q_{22}) increase as an operator spends more time in searching, after a decision aid suggests a decision. It is assumed that $c_{21} \geq c_{12}$, $c_{21} \geq c_{31}$, and $c_{12} \geq c_{32}$. Also it is assumed that c_{31} approaches c_{21}, and c_{32} approaches c_{12} as time goes.

From (3.28) and (3.29), α and β can be rewritten in terms of q_{11} and q_{22} as:

$$\alpha = \frac{c_{12}q_{22} - c_{32} - c_3(1-q_{22})}{c_{12}q_{22} + c_{21}(1-q_{11}) + c_3(q_{11}+q_{22}-1)} \tag{3.37}$$

$$\beta = \frac{(c_{12}+c_3)(1-q_{22}) + c_{32}}{c_{21}q_{11} + c_{12}(1-q_{22}) - c_3(q_{11}+q_{22}-1)} \tag{3.38}$$

The effects of the increment or the decrement of the costs and the probabilities can be expressed mathematically as partial derivatives. The partial derivatives can be shown as:

$$\frac{\partial \alpha}{\partial q_{11}} = \frac{(c_{21}-c_3)\{c_{12}q_{22}-c_{32}-c_3(1-q_{22})\}}{\{c_{12}q_{22}+c_{21}(1-q_{11})+c_3(q_{11}+q_{22}-1)\}^2} > 0 \tag{3.39}$$

$$\frac{\partial \alpha}{\partial q_{22}} = \frac{(c_{12}+c_3)(c_{32}+c_{21}q_{21}+c_3q_{11})}{\{c_{12}q_{22}+c_{21}(1-q_{11})+c_3(q_{11}+q_{22}-1)\}^2} > 0 \tag{3.40}$$

$$\frac{\partial \alpha}{\partial c_{31}} = \frac{-1}{c_{12}q_{22}+c_{21}(1-q_{11})+c_3(q_{11}+q_{22}-1)} < 0 \tag{3.41}$$

$$\frac{\partial \alpha}{\partial c_{32}} = \frac{-1}{c_{12}q_{22}+c_{21}(1-q_{11})+c_3(q_{11}+q_{22}-1)} < 0 \tag{3.42}$$

$$\frac{\partial \beta}{\partial q_{11}} = \frac{-(c_{21}-c_3)\{(c_{12}+c_3)q_{12}+c_{32}\}}{\{c_{12}q_{12}+c_{21}q_{11}-c_3(q_{11}+q_{22}-1)\}^2} < 0 \tag{3.43}$$

$$\frac{\partial \beta}{\partial q_{22}} = \frac{-(c_{12}+c_3)\{(c_{21}-c_3)q_{11}-c_{32}\}}{\{c_{12}q_{12}+c_{21}q_{11}-c_3(q_{11}+q_{22}-1)\}^2} < 0 \tag{3.44}$$

$$\frac{\partial \beta}{\partial c_{31}} = \frac{1}{c_{12}q_{12}+c_{21}q_{11}-c_3(q_{11}+q_{22}-1)} > 0 \tag{3.45}$$

$$\frac{\partial \beta}{\partial c_{32}} = \frac{1}{c_{12}q_{12}+c_{21}q_{11}-c_3(q_{11}+q_{22}-1)} > 0 \tag{3.46}$$

since α and β are positive and less than or equal to one. The numerator of 3.39 is the numerator of α multiplied by a positive number. Therefore the partial derivative $\frac{\alpha}{q_{11}}$ is positive. The numerator of 3.44 is the denominator of β minus the numerator of β, then multiplied by a negative number, therefore negative. The others are obvious.

This implies that α increases and β decreases as q_{11} increases, q_{22} increases, c_{31} decreases, or c_{32} decreases. Therefore as q_{11} and q_{22} increase and c_{31} and c_{32} increase at the same time, α has a maximum value and β has a minimum value.

$$\alpha^* = \max_t \alpha(t) \tag{3.47}$$

$$\beta^* = \min_t \beta(t) \tag{3.48}$$

We can calculate α^* and β^* if $q_{11}(t)$, $q_{22}(t)$, $c_{31}(t)$, and $c_{32}(t)$ are known. Then the corresponding intervention rule is

$$d^* = \begin{cases} \text{intervene and search until } \beta(t) \leq p_1 \leq \alpha(t) & \text{if } \beta^* \leq p_1 \leq \alpha^* \\ \text{do not intervene, and follow the decision aid} & \text{otherwise} \end{cases} \tag{3.49}$$

3.4 Practical Implementation

3.4.1 Criteria of Incident Management

The algorithm used in developing the theory of intervention depends on the expected value of consequences. The expected value criterion is used widely in most engineering problems, however, it is not intuitive or trivial whether to use this criterion in incident management or social problems. A risk averse criterion such as to minimize the worst outcome could be preferred to the neutral criterion such as to minimize the expected outcome in a weighted average sense. If a risk averse criterion would be chosen, then the optimization could be calculated again based on that criterion.

3.4.2 Assessment of Probabilities

In order to apply the theory of human intervention successfully to a practical human-machine system, we need the probabilities. These variables can be assessed objectively based on statistical data or mathematical models or subjectively by experts.

Probabilities needed are p_0, p_{ij}, and q_{ij}. p_0 is the *a priori* probability of the characteristics of an incident. It can be calculated from the incident data, if available. For example, the p_0(there is an injury) can be assigned 0.56 when there are 56 incidents involving injuries out of 100 incidents. Probabilities p_{ij} can be assessed by the reliability test and the history of its performance during incident management. Probabilities q_{ij} can be obtained by testing an operator's performance and can be improved by training. By and large, we can estimate probabilities before an incident occurs in some objective way.

3.4.3 Assessment of Costs

There are four costs needed to be considered as shown in Table 3.1: a cost c_{12} of dispatching an agent when one should not, a cost c_{21} of not dispatching it when one should be, a cost c_{31} of searching for information when one should be, and a cost c_{32} of searching for information when one should not be.

The attributes of the costs or consequences of decisions can be the fatalities and the injuries of persons involved in an incident, as well as the time delay of the traffic flow through the incident location. Even though it is clear that a quicker incident response plan can reduce the number of fatalities, injuries, and damage, the assessment of each attribute of the cost is not as objective as the assessment of probabilities. Some difficulties are as follows:

1. There exist no available data related to the incident management of the CA/T project because

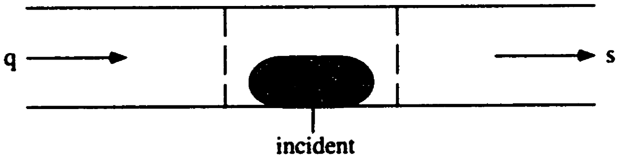


Figure 3-9: Traffic Flow during the Incident Management

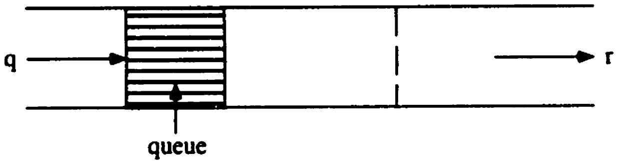


Figure 3-10: Traffic Flow after the Incident Management

the incident management plan is not finalized – the response times of agents such as MSP, BFD, and EMS are not known at the moment.

2. There is no commonly accepted systematic and objective way to estimate the value of fatalities and injuries in terms of money or time [12, 28].

3. The judgment of the *preventable damage or loss of life* by dispatching an agent immediately rather than after searching information is subjective, because, until searching is done, the incident itself is unknown, therefore the preventable damage or loss of life can not be measured in an objective way [1, 5, 20, 47].

Nevertheless, we can approximate the ratio of costs without calculating each cost. Also it is assumed that the decision aid generates alarms again and again in a certain amount of time unless the reported incident is taken care of.

Cost of Delaying Traffic Flow by Dispatching Agents Later

In this section, let us consider the time delay of the traffic flow through the incident location attributed to the time delay in an operator's decision making. Let q be the incoming traffic flow rate, the number of vehicles coming to the incident location per unit time. Let s be the outgoing traffic flow rate through the incident location during the incident management. Let r be the outgoing traffic flow rate through the incident location after the incident is cleared. It is assumed that $r > q > s$.

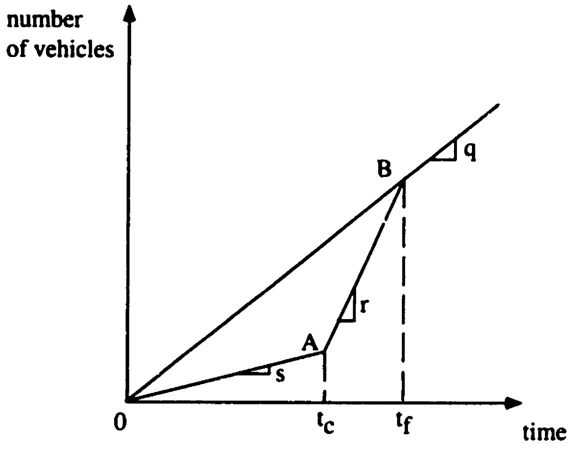


Figure 3-11: Traffic Delay during the Incident Management

During the incident management, the traffic flow is delayed and a queue is established. Suppose until time $t = t_c$, when the incident is cleared, the queue gets longer (Figure 3-9). After $t = t_c$ the traffic flow is discharged at the rate of r (Figure 3-10) and finally at time $t = t_f$ the traffic queue is cleared. This can be represented in Figure 3-11.

First, the time t_f can be expressed as

$$\begin{aligned} qt_f &= st_c + r(t_f - t_c) \\ t_f &= \frac{r-s}{r-q}t_c \end{aligned} \tag{3.50}$$

The total delay, D, in vehicles-hour (or vehicles-minute) is the area of triangle $0AB$ in Figure 3-11.

$$\begin{aligned} D &= \frac{1}{2}t_f^2 q - \frac{1}{2}t_c^2 s - \frac{1}{2}(t_f - t_c)(t_c s + t_f q) \\ &= \frac{1}{2}t_c t_f (q - s) \\ &= \frac{1}{2}\frac{(q-s)(r-s)}{r-q}t_c^2 \end{aligned} \tag{3.51}$$

Suppose an incident is cleared in time t_c if an operator dispatches agents immediately. Then the incident can be cleared in time $t_c + t_d$ if an operator dispatches agents time t_d later. Therefore the additional traffic delay ΔD caused by the time t_d, is

$$\begin{aligned} \Delta D &= \frac{1}{2}\frac{(q-s)(r-s)}{r-q}(t_c + t_d)^2 - \frac{1}{2}\frac{(q-s)(r-s)}{r-q}t_c^2 \\ &= \frac{1}{2}\frac{(q-s)(r-s)}{r-q}(2t_c t_d + t_d^2) \end{aligned} \tag{3.52}$$

If we know the cost of delaying traffic flow per vehicle per time, C_t in a unit of *dollar/(vehicle·hour)*, then the cost of delaying the traffic flow by dispatching agents later by time t_d (hour) is

$$c_{traffic}(t_d) = \frac{1}{2} C_t \frac{(q-s)(r-s)}{r-q} (2t_c t_d + t_d^2) \tag{3.53}$$

Cost of Preventable Fatalities, Injuries, and Damage

Suppose we know the number of fatalities n_f, the degree of injuries n_i, and the amount of damage n_d if an operator dispatches agents immediately, and the number of fatalities $\tilde{n_f}(t_d)$, the degree of injuries $\tilde{n_i}(t_d)$, and the amount of damage $\tilde{n_d}(t_d)$ if an operator dispatches agents later by time t_d. Also we know a unit cost C_f of a fatality (*dollar/fatality*), a unit cost C_i of an injury (*dollar/injury*), and a unit cost C_d of damage (*dollar/damage*). Then we can compute the cost of preventable fatalities, injuries, and damage by dispatching agents at a later time t_d when they should be dispatched immediately as

$$c_{preventable}(t_d) = C_f(\tilde{n_f}(t_d) - n_f) + C_i(\tilde{n_i}(t_d) - n_i) + C_d(\tilde{n_d}(t_d) - n_d) \tag{3.54}$$

Cost of Not Dispatching When Agents Should Be Dispatched

We assume that the decision aid generates an alarm again every interval of time t_a if there is no proper response from an operator. Then the cost of not dispatching an agent when it should be dispatched is $c_{traffic}(t_a) + c_{preventable}(t_a)$. Therefore

$$c_{21} = c_{traffic}(t_a) + c_{preventable}(t_a) \tag{3.55}$$

Cost of Searching When Agents Should Be Dispatched

Let t_s be the searching time spent by an operator. During time period t_s, the incident can be worsen and traffic can be delayed. By using the previous results, we can express as:

$$c_{31} = c_{traffic}(t_s) + c_{preventable}(t_s) \tag{3.56}$$

Cost of Dispatching an Agents Unnecessarily

Let us assume that the agent arrives at the reported location, once it is dispatched. This means that the dispatched agent is not available, while it moves to the reported location, for an incident which may happen elsewhere during that time period. Therefore the cost of unnecessary dispatch is the cost of not responding to an incident which can happen elsewhere while the agent is not available.

Suppose the number of incidents per unit time n_a (*number of incident/hour*) is known and the average response time for an agent (the time taken from its station to an incident location) is given as t_r (*hour*). Then

$$c_{12} = c_{unnecessary}(t_r) = n_a t_r \left\{ c_{traffic}\left(\frac{t_r}{2}\right) + c_{preventable}\left(\frac{t_r}{2}\right) \right\} \tag{3.57}$$

Cost of Searching Unnecessarily

The cost for an operator to search information when he or she needs not is the cost of not responding to other incidents during the searching time. By the same reason,

$$c_{32} = c_{unnecessary}(t_s) = n_a t_s \left\{ c_{traffic}\left(\frac{t_s}{2}\right) + c_{preventable}\left(\frac{t_s}{2}\right) \right\} \tag{3.58}$$

where t_s is the searching time.

3.4.4 Approximations of Ratios of Costs

As we see α, β in (3.28) and (3.29), α, β can be expressed the ratios of the costs. Therefore we can approximate α, β numerically, without finding the numerical value of each cost, by approximating the ratios of the costs.

By expanding each cost by Taylor's series and ignoring high order terms, we can express costs as:

$$\begin{aligned} c_{12} &\approx k \cdot 1/2 \cdot n_a t_r^2 \\ c_{21} &\approx k \cdot t_a \\ c_{31} &\approx k \cdot t_s \\ c_{32} &\approx k \cdot 1/2 \cdot n_a t_s^2 \end{aligned} \tag{3.59}$$

where k is a constant. We can approximate the ratios as

$$\frac{c_{12}}{c_{21}} \approx \frac{n_a t_r^2}{2t_a} \tag{3.60}$$

$$\frac{c_{31}}{c_{21}} \approx \frac{t_s}{t_a} \tag{3.61}$$

$$\frac{c_{32}}{c_{21}} \approx \frac{n_a t_s^2}{2t_a} \tag{3.62}$$

Now we can rewrite α, β in (3.28) and (3.29), and restate the rule of intervention in (3.25), (3.26), (3.30), (3.31), and (3.32) with the above ratios. (3.25) can be rewritten as:

$$\frac{c_{32}}{c_{21}} + \left(\frac{c_{31}}{c_{21}} - \frac{c_{32}}{c_{21}}\right) \frac{c_{12}/c_{21} \cdot q_{11} + q_{12}}{c_{12}/c_{21} + 1} < (q_{11} + q_{22} - 1)\frac{c_{12}/c_{21}}{c_{12}/c_{21} + 1} \tag{3.63}$$

(3.26) can be rewritten as:

$$\frac{c_{32}}{c_{21}} + \left(\frac{c_{31}}{c_{21}} - \frac{c_{32}}{c_{21}}\right) \frac{c_{12}/c_{21}(2q_{12} - q_{11}) + q_{12}}{c_{12}/c_{21} + 1} < (q_{11} + q_{22} - 1)\frac{c_{12}/c_{21}}{c_{12}/c_{21} + 1} \tag{3.64}$$

α in (3.28) can be expressed as:

$$\alpha = \frac{c_{12}/c_{21} \cdot q_{22} + c_{32}/c_{21} - (c_{31}/c_{21} - c_{32}/c_{21})q_{12}}{c_{12}/c_{21} \cdot q_{22} + q_{21} + (c_{31}/c_{21} - c_{32}/c_{21})(q_{11} + q_{22} - 1)} \tag{3.65}$$

and β in (3.29) as:

$$\beta = \frac{c_{12}/c_{21} \cdot q_{12} + c_{32}/c_{21} + (c_{31}/c_{21} - c_{32}/c_{21})q_{12}}{q_{11} + c_{12}/c_{21} \cdot q_{12} - (c_{31}/c_{21} - c_{32}/c_{21})(q_{11} + q_{22} - 1)} \tag{3.66}$$

3.5 Technical Proofs

Proof A

$\frac{c_{12}q_{12}}{c_{12}q_{12}+c_{21}q_{11}} < \frac{c_{12}}{c_{12}+c_{21}} < \frac{c_{12}q_{22}}{c_{12}q_{22}+c_{21}q_{21}}$ if and only if[3] $q_{11} + q_{22} > 1$.

$$
\begin{aligned}
& 1 < q_{11} + q_{22} \\
\Longleftrightarrow\, & 1 - q_{11} - q_{22} + q_{11}q_{22} < q_{11}q_{22} \\
\Longleftrightarrow\, & q_{12}q_{21} < q_{11}q_{22} \\
\Longleftrightarrow\, & c_{21}q_{12}q_{21} + c_{12}q_{12}q_{22} < c_{21}q_{11}q_{22} + c_{12}q_{12}q_{22} \\
\Longleftrightarrow\, & c_{12}q_{12}(c_{21}q_{21} + c_{12}q_{22}) < c_{12}q_{22}(c_{21}q_{11} + c_{12}q_{12}) \\
\Longleftrightarrow\, & \frac{c_{12}q_{12}}{c_{12}q_{12} + c_{21}q_{11}} < \frac{c_{12}q_{22}}{c_{12}q_{22} + c_{21}q_{21}}
\end{aligned} \tag{3.67}
$$

$$
\begin{aligned}
& 1 < q_{11} + q_{22} \\
\Longleftrightarrow\, & q_{12} + q_{22} < q_{11} + q_{22} \\
\Longleftrightarrow\, & q_{12} < q_{11} \\
\Longleftrightarrow\, & c_{21}q_{12} < c_{21}q_{11} \\
\Longleftrightarrow\, & c_{21}q_{12} + c_{12}q_{12} < c_{21}q_{11} + c_{12}q_{12} \\
\Longleftrightarrow\, & c_{12}q_{12}(c_{12} + c_{21}) < c_{12}(c_{12}q_{12} + c_{21}q_{11}) \\
\Longleftrightarrow\, & \frac{c_{12}q_{12}}{c_{12}q_{12} + c_{21}q_{11}} < \frac{c_{12}}{c_{12} + c_{21}}
\end{aligned} \tag{3.68}
$$

$$
\begin{aligned}
& 1 < q_{11} + q_{22} \\
\Longleftrightarrow\, & q_{11} + q_{21} < q_{11} + q_{22} \\
\Longleftrightarrow\, & q_{21} < q_{22} \\
\Longleftrightarrow\, & c_{21}q_{21} < c_{21}q_{22} \\
\Longleftrightarrow\, & c_{21}q_{21} + c_{12}q_{22} < c_{21}q_{22} + c_{12}q_{22} \\
\Longleftrightarrow\, & c_{12}(c_{12}q_{22} + c_{21}q_{21}) < c_{12}q_{22}(c_{12} + c_{21}) \\
\Longleftrightarrow\, & \frac{c_{12}}{c_{12} + c_{21}} < \frac{c_{12}q_{22}}{c_{12}q_{22} + c_{21}q_{21}}
\end{aligned} \tag{3.69}
$$

---

[3] $\Longleftrightarrow$ means if and only if.

Chapter 4

Design of Human-Computer Interfaces

4.1 Human-Computer Interaction

Human-computer interaction is an exchange of information between a human operator and a computer. The interaction involves a two-way exchange of information in the form of an operator's *decisions* presented as inputs to the computer and *responses* and *messages* from the computer as shown in Figure 4-1. A human-computer interface is a tool that achieves a desirable human-computer interaction.

Traditionally, human-computer interfaces were implemented by devices of a fixed format such as dials, levers, or gauges. Now a human-computer interface, with sophisticated software, is flexibly designed and displayed on a computer monitor or a CRT in the form of so-called a *window box* and a *dialog box*.

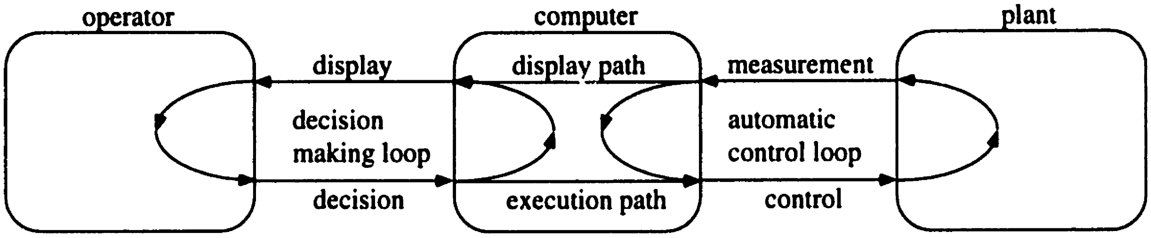


Figure 4-1: Diagram of Human-Computer Interaction

4.2 Principles of Human-Computer Interface Design

A human-computer interface is to provide a dialog between a human operator and a computer. In designing a human-computer interface, human factors principles must be considered to be effective. Williges [56] suggests seven principles to consider in human-computer interface design.

1. Compatibility: Minimize the amount of information recording that will be necessary.
2. Consistency: Minimize the difference in dialogue both within and across various human-computer interfaces.
3. Memory: Minimize the amount of information that the human operator must maintain in short-term memory[1].
4. Structure: Assist operators in developing a conceptual representation of the structure of the system so that they can navigate through the interface.
5. Feedback: Provide operators with feedback and error correction capabilities.
6. Workload: Keep operator's mental workload within acceptable limits.
7. Individualization: Accommodate individual differences among operators through automatic adaptation or operator tailoring of the interface.

4.3 Considerations in Designing Human-Computer Interfaces

There are many things to be considered to make a human-computer interface. For the most part there is no one best way to do it, but below are discussed several considerations for displaying decisions under uncertainties [36, 42, 46].

4.3.1 Users

The most important consideration in designing a human-computer interface is the human operators, especially who they are and how much they are familiar with a computer. Some thing which are obvious to a designer (maybe a college graduate software engineer) of human-computer interfaces are not obvious to some people who have a little experience with a computer.

---

[1] The human memory system has been conceptualized as three subsystems: *sensory storage*, *short-term memory*, and *long-term memory*. Short-term memory (also called working memory) is the gateway to long-term memory from sensory storage and the place where computations and reasoning are done [43].

Table 4.1: Scale of Degree of Automation from Sheridan [44]

```
 1. The computer offers no assistance, human must do it all.
 2. The computer offers a complete set of action alternatives, and
 3.     narrows the selection down to a few, or
 4.     suggests one, and
 5.   executes that suggestion if the human approves, or
 6.   allows the human a restricted time to veto before automatic execution, or
 7.   executes automatically, then necessarily informs the human, or
 8.   informs him after execution only if he asks, or
 9.   informs him after execution if the computer decides to.
10. The computer decides everything and acts autonomously.
```

4.3.2 Tasks

The task to be achieved by a human-computer interaction/interface needs to be considered as to whether it is a time critical task, whether it is for just providing information to operators, or it is used to make a decision. If it is time critical, the contents need to be simple and compact. For decision making, it may provide consequences for each decision alternatives or for some alternatives which operators request.

4.3.3 Degree of Supervisory Control

Table 4.1 lists 10 levels of automation, focusing on the human-computer interactions in supervisory control [44]. This table can be used for designing of human-computer interfaces and for specifying the operators' role and responsibility. It is necessary to consider which information should be provided from the viewpoint of the degree of automation.

4.3.4 Transparency

Hollnagel[11] argues that Human-computer interaction or interface should not be a prosthesis which makes an operator interact with a computer, but rather a medium that makes an operator experience the task or the decision, where the tool or medium itself is transparent.

4.3.5 Presentation of Information

It is shown that decision making can be affected by the manner in which information is presented or *framed.* As an example, consider the following decisions and select one preferred medical treatment from each question [54].

`Decision (i) (Survival Frame) Choose between:`
`Surgery: Of 100 people having surgery 90 live through the post-operative period, 68 are alive at the end of the first year, and 34 are alive at the end of five years.`
`Radiation therapy: Of 100 people having radiation therapy all live through the treatment, 77 are alive at the end of one year, and 22 are alive at the end of five years.`

`Decision (ii) (Mortality Frame) Choose between:`
`Surgery: Of 100 people having surgery 10 die during surgery or the post operative period, 32 die by the end of the first year, and 66 die by the end of five years.`
`Radiation therapy: Of 100 people having radiation therapy, none die during treatment, 23 die by the end of one year, and 78 die by the end of five years.`

Experimental results [54] showed that the overall percentage of respondents who favored radiation therapy rose from 18% in the survival frame to 44% in the mortality frame. A decision can be made in a totally different direction as the way to present it varies.

4.3.6 Risk Averse and Risk Taking Decisions

People take chances depending on the situation. Depending on the situation, they make a risky decision or a safe decision. As an example, consider the following decisions [54].

`Decision (i) Choose between:`
`A. a sure gain of $250`
`B. 25% chance to gain $1,000 and 75% chance to gain nothing`

`Decision (ii) Choose between:`
`C. a sure loss of $250`
`D. 25% chance to lose $1,000 and 75% chance to lose nothing`

According to Tversky's results, 84% of respondents favored A and 87% favored D. This is a common decision making pattern: *risk averse* for potential gains and *risk seeking* for potential losses – except when the probability of winning or losing is small.

If only the expected momentary value is considered, there is no difference A and B, and C and D. Decision (i) gives the expected gain $250 and decision (ii) gives the expected loss $250 regardless of choices. Mathematically speaking, the decision outcome by maximizing the gain should be the same as that by minimizing the loss. But humans interpret them differently in decision making and have different attitudes toward the risk for different tasks.

4.3.7 Uncertainties

Uncertainty also alters the way that people make decisions. The following Ellsberg paradox [7] shows the effect of uncertainty.

```
Consider a barrel which contains a mixture of 90 red, blue, and yellow balls.
Thirty  of balls are red, and the remaining 60 are a mixture of blue and yellow,
but  the proportion of blue and yellow is unknown. A single ball is randomly
drawn  from the barrel. Examine each decision, then indicate an option you prefer.

Decision (i) Choose between:
A: win $1,000 if a red ball is chosen.
B: win $1,000 if a blue ball is chosen.

Decision (ii) Choose between:
C: win $1,000 if either a red or a yellow ball is chosen.
D: win $1,000 if either a blue or a yellow ball is chosen.
```

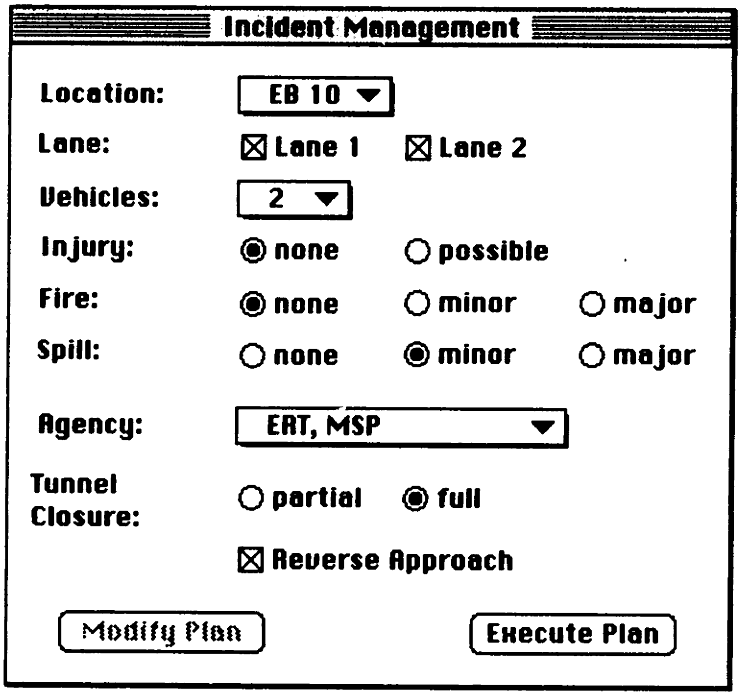
Many people prefer A in the decision (i) and D in the decision (ii). If a decision maker is consistent, he or she should choose A and C or B and D, because adding a chance of a yellow ball does not change the gain in the expected value in decision (i) and decision (ii).

4.3.8 Time Pressure

It can be expected that the lack of time to evaluate information alters the way people make decisions. Under time pressure, people tend to indicate greater weight given to negative and more important attributes, greater variability of judgments, and to use a smaller number of attributes [9]. Also time pressure makes human search fewer alternatives [19].

4.4 Incident Management Dialog for the CA/T project

4.4.1 Current Design



Location: EB 10 ▼

Lane: ☒ Lane 1 ☒ Lane 2

Vehicles: 2 ▼

Injury: ● none ○ possible

Fire: ● none ○ minor ○ major

Spill: ○ none ● minor ○ major

Agency: ERT, MSP ▼

Tunnel Closure: ○ partial ● full

☒ Reverse Approach

Figure 4-2: Incident Management Dialog Box Based on the Current Design Document

Figure 4-2 shows an incident management dialog box based on the current CA/T design document [49]. The upper half part shows the characteristics of an incident which is detected by a decision aid (IPCS) – an incident location, the number of vehicles, the possibility of injured persons, fire, and hazardous material spill. The presentation format of injury, fire, and spill is discrete, for example, no injury or injury, no fire or minor fire or major fire, and no spill or minor spill or major spill. The lower half part of the dialog shows a response plan: agents to be dispatched, how they approach the incident location, and whether or not to close the tunnel. A plan is suggested initially by a computer based on its measurements.

Once given information about an incident, an operator evaluates it by assigning subjective probabilities or confidence values for each item, and then make a decision whether to search or to execute a plan suggested by a decision aid.

As discussed earlier, the subjective probabilities can be wrongly estimated by the format of presentation and the time pressure. There are many possible problems with the current human-computer interface (HCI), such as:

1. It does not give an operator the estimates of error of detection. Since the decision aid presents the states discretely, an operator has to make his or her estimate of error of detection based on little or no information.

2. Different operators can make different response plans, because each operator judges the estimated error differently.

3. Inconsistent decisions can cause confusion among operators and to the public, and can lead a decrease in overall performance of incident management. At the OCC of the CA/T project, there will be up to 30 operators (3 shifts and 10 operators per shift). It is not desirable for 30 operators to make 30 different response plans for the same incident.

4.4.2 New Proposed Design

To prevent such an ambiguity in the current HCI and to make consistent decisions as a team, it is necessary to close the decision making loop in Figure 4-1, which is not to be implemented in the current design of human-machine interfaces. The necessary functions for a new human-computer interface are:

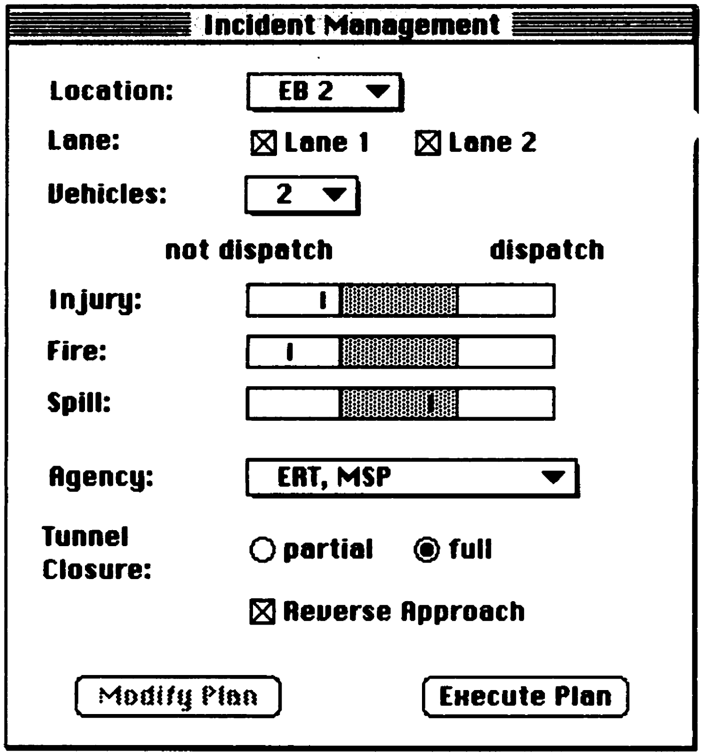
1. A new HCI should give an objective estimate of error of detection. The explicit presentation of an estimate of error can prevent an operator from a biased subjective estimation.

2. The presentation format itself should not cause any biased judgment. A new HCI should provide a tool to make a *neutral* decision, not risk averse or risk seeking.

3. The information shown on a new HCI should guide different operators to make the same decision for the same incident.

Based on the human intervention model developed in Chapter 3, a new human-computer interface for the incident management is proposed as shown in Figure 4-3. The upper part and the lower part of the HCI are the same as the current HCI design. The upper part shows an incident location and possible lanes blocked by the detected incident. The lower part shows a suggested response plan.

The middle part of the HCI shows the characteristics of an incident in terms of a response plan – whether or not to dispatch a corresponding agent or to search additional information. When a dot lies in the left section of a bar, it means not to dispatch a corresponding agent. When a dot lies in the middle section of a bar, it means to search additional information. When a dot lies in the right section of a bar, it means to dispatch a corresponding agent. Also, the distance from the ends of a bar indicates the confidence in an objective way, expressed in the objective functions shown in Chapter 3. The provision of a response plan with an estimate of error and whether or not to search additional information will guide an operator to make a better and more timely decision consistently under time pressure.



Location: EB 2

Lane: ☒ Lane 1 ☒ Lane 2

Vehicles: 2

Injury:

Fire:

Spill:

Agency: ERT, MSP

Tunnel Closure: ○ partial ● full

☒ Reverse Approach

Figure 4-3: New Incident Management Dialog Box Based on the Human Intervention Model

Chapter 5

Human-in-the-Loop Experiments

5.1 Objectives

As discussed in Chapter 2, an operator at the CA/T project makes a final response plan based on a response plan suggested by a decision aid. The quality of the final response plan depends on the performance level of a computer, the performance level of an operator, and human-computer interactions/interfaces. The objectives of this series of human-in-the-loop experiments are to evaluate the effect of the human-computer interaction/interface on the overall performance of a human-machine system, in the context of incident management of the CA/T project. The experiments are focused on how a human operator intervenes in a decision aid with the current human-computer interface (shown in Figure 4-2), and whether the performance of the incident management could be increased with the new human-computer interface developed (shown in Figure 4-3).

5.2 Experiment Setup

5.2.1 Experiments

Four experiments were carried out with the developed incident management simulator (see Appendix A). Each experiment had a different combination of human-computer interface, performance level of a decision aid, and performance level of an operator. The performance of a decision aid and the performance of an operator mean the probabilities of detecting the characteristics of an incident correctly, respectively.

Two human-computer interfaces were considered. The human-computer interface A (Figure 4-2) was designed based on the current CA/T design documents, and the human-computer interface B

Table 5.1: Experiments

EXPERIMENT	HCI	PERFORMANCE
1	HCI A	decision aid 75%, operator 60%
2	HCI A	decision aid 75%, operator 90%
3	HCI B	decision aid 75%, operator 60%
4	HCI B	decision aid 75%, operator 90%

(Figure 4-3) was designed based on the theory of human intervention as discussed in Chapter 4. In terms of performance, two cases were considered: (1) when the performance of the decision aid (75%) was better than that of the operator (60%) and (2) when the performance of the decision aid (75%) was worse than that of the operator (90%).

Once an incident happened, a decision aid was assumed to detect it immediately and generate a response plan correctly based on the its detection, i.e., a response plan was correct if the measurement was correct and a response plan was wrong if the measurement was wrong.

5.2.2 Trials

Each experiment consisted of eighteen trials. One trial had one incident. An incident could be characterized by the incident location, the number of lanes blocked by the incident, the existence of injured persons, the existence of fire, existence of spill, and the time when it happened. There could be many different types of incident, but eighteen types were considered for experiments as shown in Table 5.2 and 5.3.

An incident occurred at the very beginning of a simulation. An incident location was randomly selected, which could be anywhere inside the tunnel. Lanes blocked by an incident were randomly selected, too.

5.2.3 Sequence of Trials

To nullify the learning effect, the sequence of experiments as well as the sequence of trials were randomly mixed as shown in Table 5.4 and 5.5.

5.2.4 Subjects

Selection

Ten subjects were hired among graduate and undergraduate students at the Massachusetts Institute of Technology. Each subject received a fixed payment based on participation time at 7.5 dollars per

Table 5.2: Trials for Experiment 1 and 3

TRIAL	LOCATION	LANES	VEHICLE	INJURY	FIRE	SPILL
11	14	2	2	no	no	no
12	11	1	2	no	no	minor
13	12	1	2	no	no	major
14	16	2	2	no	minor	no
15	4	2	2	no	minor	minor
16	15	2	2	no	minor	major
17	8	1,2	2	no	major	no
18	3	1,2	2	no	major	minor
19	5	1,2	2	no	major	major
1a	6	2	2	yes	no	no
1b	6	1	2	yes	no	minor
1c	15	1	2	yes	no	major
1d	11	2	2	yes	minor	no
1e	14	2	2	yes	minor	minor
1f	2	1,2	2	yes	minor	major
1g	2	1,2	2	yes	major	no
1h	4	1	2	yes	major	minor
1i	9	1	2	yes	major	major

Table 5.3: Trials for Experiment 2 and 4

TRIAL	LOCATION	LANES	VEHICLE	INJURY	FIRE	SPILL
21	13	1	2	no	no	no
22	2	2	2	no	no	minor
23	7	1	2	no	no	major
24	19	1	2	no	minor	no
25	14	1	2	no	minor	minor
26	2	2	2	no	minor	major
27	7	2	2	no	major	no
28	5	1,2	2	no	major	minor
29	4	1	2	no	major	major
2a	18	2	2	yes	no	no
2b	17	1	2	yes	no	minor
2c	6	1,2	2	yes	no	major
2d	8	1	2	yes	minor	no
2e	4	1	2	yes	minor	minor
2f	19	2	2	yes	minor	major
2g	10	1	2	yes	major	no
2h	11	2	2	yes	major	minor
2i	12	2	2	yes	major	major

Table 5.4: Sequence of Experiments

SUBJECT	SEQUENCE OF EXPERIMENTS
A	1, 2
B	2, 1
C	2, 1
D	1, 2
E	2, 1
F	3, 4
G	4, 3
H	4, 3
I	3, 4
J	4, 3

Table 5.5: Sequence of Trials

SUBJECT	EXP.	SEQUENCE OF TRIALS
A	1	1f,11,16, 1i, 17, 1a, 1h, 12, 19, 1g, 14, 1e, 1d, 13, 15, 18, 1c, 1d
	2	23, 2g, 21, 22, 27, 29, 2i, 24, 26, 28, 2c, 2e, 2h, 25, 2a, 2d, 2f, 2b
B	1	12, 1e, 1a, 1f, 11, 13, 1b, 17, 19, 1d, 1g, 1i, 15, 14, 18, 1h, 16, 1c
	2	2d, 27, 2e, 23, 25, 2f, 2c, 2g, 29, 2i, 22, 26, 21, 2a, 2b, 2h, 28, 24
C	1	13, 16, 19, 11, 1b, 1f, 1c, 12, 1d, 17, 1g, 15, 1h, 1i, 1a, 18, 1e, 14
	2	23, 24, 2d, 2b, 27, 2e, 2h, 25, 29, 2c, 2i, 2g, 21, 2f, 28, 2a, 22, 26
D	1	1h, 11, 1a, 1g, 13, 12, 15, 1b, 18, 14, 17, 19, 1e, 1c, 1d, 1f, 16, 1i
	2	21, 25, 2e, 29, 2g, 2d, 24, 26, 2h, 27, 23, 2i, 28, 22, 2b, 2a, 2f, 2c
E	1	16, 1c, 12, 1d, 1i, 17, 19, 18, 11, 14, 1f, 13, 1e, 1a, 1h, 15, 1g, 1b
	2	28, 2b, 29, 2f, 22, 25, 27, 2a, 2i, 2h, 23, 2e, 2c, 24, 2d, 21, 26, 2g
F	3	1f,11,16, 1i, 17, 1a, 1h, 12, 19, 1g, 14, 1e, 1d, 13, 15, 18, 1c, 1d
	4	23, 2g, 21, 22, 27, 29, 2i, 24, 26, 28, 2c, 2e, 2h, 25, 2a, 2d, 2f, 2b
G	3	12, 1e, 1a, 1f, 11, 13, 1b, 17, 19, 1d, 1g, 1i, 15, 14, 18, 1h, 16, 1c
	4	2d, 27, 2e, 23, 25, 2f, 2c, 2g, 29, 2i, 22, 26, 21, 2a, 2b, 2h, 28, 24
H	3	13, 16, 19, 11, 1b, 1f, 1c, 12, 1d, 17, 1g, 15, 1h, 1i, 1a, 18, 1e, 14
	4	23, 24, 2d, 2b, 27, 2e, 2h, 25, 29, 2c, 2i, 2g, 21, 2f, 28, 2a, 22, 26
I	3	1h, 11, 1a, 1g, 13, 12, 15, 1b, 18, 14, 17, 19, 1e, 1c, 1d, 1f, 16, 1i
	4	21, 25, 2e, 29, 2g, 2d, 24, 26, 2h, 27 23, 2i, 28, 22, 2b, 2a, 2f, 2c
J	3	16, 1c, 12, 1d, 1i, 17, 19, 18, 11, 14, 1f, 13, 1e, 1a, 1h, 15, 1g, 1b
	4	28, 2b, 29, 2f, 22, 25, 27, 2a, 2i, 2h, 23, 2e, 2c, 24, 2d, 21, 26, 2g

Table 5.6: Response Plan for Experiments

CONDITION	PLAN
If there is only one vehicle without injury	Dispatch ERT
If there is more than one vehicle	Dispatch ERT and MSP
If there is a possible injury	Dispatch ERT, MSP, and EMS
If there is a minor fire or a minor spill	Dispatch ERT and MSP
If there is a minor fire or a minor spill with a possible injury	Dispatch ERT, MSP, and EMS
If there is a major fire or a major spill	Dispatch ERT, MSP, and BFD
If there is a major fire or a major spill with a possible injury	Dispatch ERT, MSP, BFD, and EMS

hour plus a bonus based on his or her performance. The bonus was determined by each subject's performance points, at the rate of one dollar per point.

Once an applicant agreed to be a subject for this experiment with the above conditions, the applicant was asked to sign the subject consent form shown in Appendix D.

They were divided into two groups in order to reduce the learning effect from one experiment to another experiment[1]. One group did experiment 1 and 2 and the other group did experiment 3 and 4. For the convenience, subjects who did experiment 1 and 2 were named A, B, C, D, and E, and the other subjects F, G, H, I, and J.

Training

Subjects were trained using an oral brief, a demonstration, a tutorial manual, and some practice trials. Before the practice, a subject was asked to read the tutorial manual [16] for an hour. and to memorize the set of response plans in Table 5.6. The manual contained a detailed explanation of the structure and the operation of the simulator, included a summary of the commands, and explained the subject's role in experiments. The brief and demonstration were administered by the experimenter. In particular, a subject was given an explanation of the simulator and how to use it, and told the purpose of the experiment. After a subject understood, a subject carried out six practice trials which were randomly selected from the set of eighteen trials.

During the training, it was clearly stated and emphasized that an incident should be cleared as quickly and correctly as possible, and in no longer than fifteen minutes. Also, it was explained how performance was measured.

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[1] There are possibilities of transferring learning from one experiment to another. A positive transfer means that the second experiment benefits from the first experiment when the same person performs both experiments. Negative transfer means that the condition performed second may be at a disadvantage as a result of the condition performed first [37].

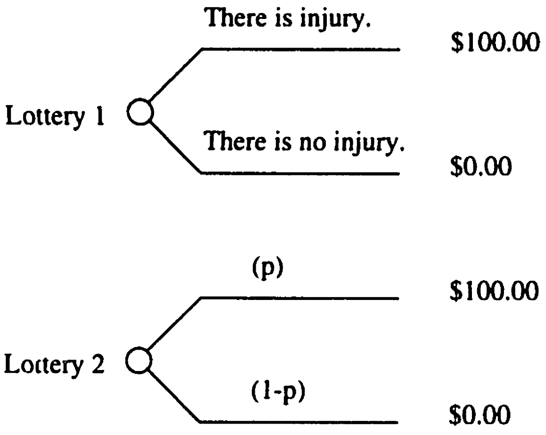

Figure 5-1: Decision Tree Representation for Assessing Subjective Probability with Equivalent-Lottery Method

5.2.5 Task of Experimental Subjects

As soon as an alarm was noticed, a subject needed to acknowledge it. Then the decision aid provided some information about the detected incident through the incident management dialog box (See Appendix A for the details). Since the measurement was not perfect, the information provided was not necessarily correct. To make a more correct response plan, more information could be collected through the information window. But there was a *time delay* in collecting information through the information window, and the information collected through the information window might be not correct.

Therefore it was a subject's task to estimate the accuracy of information, to determine costs of dispatching and not-dispatching each agent, and to make a correct response plan – dispatching only necessary agents – to clear a given incident within the time limit of 15 minutes.

5.3 Experiment Results

5.3.1 Assessment of Subjective Probabilities

At the end of experiment 1 and 2, subjects A, B, C, D, and E were asked to estimate subjective probabilities of the characteristics of an incident when the given information was in conflict (see Appendix E). For example, it was asked what the probability of injury would be if the decision aid said that there was injury and an operator observed that there was no injury.

The *equivalent-lottery* method [7] was used to assess the subjective probabilities. The assessment

Table 5.7: Subjective Probability Estimation of Given Information: Case 1 was when the decision aid said that there was no injury and the operator's observation said that there was injury in experiment 1. Case 2 was when the decision aid said that there was injury and the operator's observation said that there was no injury in experiment 1. Case 3 was when the decision aid said that there was no injury and the operator's observation said that there was injury in experiment 2. Case 4 was when the decision aid said that there was injury and the operator's observation said that there was no injury in experiment 2.

SUBJECT	CASE 1	CASE 2	CASE 3	CASE 4
A	0.45	0.55	0.60	0.40
B	0.40	0.62	0.90	0.10
C	0.42	0.75	0.85	0.43
D	0.50	0.50	0.90	0.15
E	0.40	0.56	0.85	0.10
TRUE VALUE	0.33	0.67	0.75	0.25

procedure for the subjective probabilities was to ask each subject to compare two lottery-like games, each of which could result in either getting \$0 or getting \$100 (Figure 5-1). First, a subject was given a situation; for example, suppose the decision aid said that there was injury and the observation said that there was no injury. Then a subject was asked to compare lottery 1 with lottery 2.

`Lottery 1:`
`Win $100 if there is injury`
`Win $0 if there is no injury`

`Lottery 2:`
`Win $100 with known probability p`
`Win $0 with known probability 1-p`

The procedure was to adjust the probability p of lottery 2 until the subject was indifferent between lottery 1 and 2. Indifference in this case meant that the subject had no preference between the two lotteries. If a subject was indifferent, then his or her subjective probability that there was injury must be p.

The results in Table 5.7 shows that the subjects did not estimate the true state[2] correctly when

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[2] *The true values* are calculated by Bayes' rule as shown in Section 3.3.3. By the notations used in Section 3.3.3, we can assign as $p_0 = 0.5$, $p_{11} = p_{22} = 0.75$, $p_{12} = p_{21} = 0.25$, $q_{11} = q_{22} = 0.6$, and $q_{12} = q_{21} = 0.4$ for case 1 and 2 (for the experiment 1), and $q_{11} = q_{22} = 0.9$, and $q_{12} = q_{21} = 0.1$ for case 3 and 4 (for the experiment 2). For case 1, since the decision aid said that there was no injury, it implies that $y = X_2$ and $p_1 = (0.25 \times 0.5)/(0.25 \times 0.5 + 0.75 \times 0.5) = 0.25$ by (3.12). Also since an operator's observation said there was injury, $z = X_1$ and $p_2 = (0.6 \times 0.25)/(0.6 \times 0.25 + 0.4 \times 0.75) = 1/3$ by (3.13). By the same way, we can compute the true values for case 2, 3, and 4. For case 2, $p_1 = 0.75$ and $p_2 = (0.4 \times 0.75)/(0.4 \times 0.75 + 0.6 \times 0.25) = 2/3$. For case 3, $p_1 = 0.25$ and $p_2 = (0.9 \times 0.25)/(0.9 \times 0.25 + 0.1 \times 0.75) = 0.75$. For case 4, $p_1 = 0.75$ and $p_2 = (0.1 \times 0.75)/(0.1 \times 0.75 + 0.9 \times 0.25) = 0.25$.

Table 5.8: Threshold Probability for Decision-Making

SUBJECT	PROBABILITY	RATIO OF COSTS c_{21}/c_{12}
A	0.3	2.333
B	0.4	1.500
C	0.5	1.000
D	0.4	1.500
E	0.5	1.000

given information was contradictory.

5.3.2 Strategy for Making a Response Plan

At the end of the experiment 1 and 2, subjects A, B, C, D, and E were asked to whether they would dispatch an agent for a given probability of certain events. The question might be, for example, "Would you dispatch an EMS if the probability of injury is p?" By successively asking the question with different p's, a subject's probability for dispatching an agent could be found.

As shown in Table 5.8, each subject had a different threshold probability. From the perspective of the decision analysis, the ratio of costs c_{21}/c_{12} can be calculated based on the probability. From (3.16), we can show

$$\frac{c_{21}}{c_{12}} = \frac{1-p}{p} \tag{5.1}$$

Subjects showed different ratio of costs which resulted in different ways of making response plans as shown in Table 5.8.

5.3.3 Behavior of Searching Information

Subjects A, B, C, D, and E freely sought additional information in the experiment 1 and 2, as summarized in Table 5.9 and 5.10. In the experiment 3 and 4, subjects F, G, H, I, and J were confined to search what was recommended by the decision aid, as shown in Table 5.11 and 5.12. All individual data are shown in Appendix G.

The results of searching behavior in experiments 1 and 2 show diverse searching behavior. Subjects D and E did not search any information at all during experiment 1 and 2, and subject B did not search any information during experiment 1, while subjects A and C sought information during both experiment 1 and 2.

Subject A sought a corresponding information category when the decision aid said there was no

Table 5.9: Behavior of Searching Information in Experiment 1: Categories indicate the information given by a decision aid. The numerator of the ratio shows the number of an operator's searches for the corresponding information, and the denominator is the number of the corresponding category detected and noticed by the decision aid. For example, minor fire 4/6 indicates that the subject sought fire 4 times and the decision aid noticed minor fire 6 times.

		SUBJECT A			
no injury	10/10	no fire	4/4	no spill	5/9
possible injury	0/8	minor fire	6/9	minor spill	3/6
		major fire	0/5	major spill	0/3
		SUBJECT B			
no injury	0/10	no fire	0/8	no spill	0/7
possible injury	0/8	minor fire	0/5	minor spill	0/5
		major fire	0/5	major spill	0/6
		SUBJECT C			
no injury	3/5	no fire	0/8	no spill	0/5
possible injury	10/13	minor fire	1/6	minor spill	2/5
		major fire	0/4	major spill	2/8
		SUBJECT D			
no injury	0/9	no fire	0/7	no spill	0/5
possible injury	0/9	minor fire	0/4	minor spill	0/6
		major fire	0/5	major spill	0/7
		SUBJECT E			
no injury	0/9	no fire	0/7	no spill	0/7
possible injury	0/9	minor fire	0/6	minor spill	0/6
		major fire	0/7	major spill	0/5
		TOTAL			
no injury	13/43	no fire	4/34	no spill	5/33
possible injury	10/37	minor fire	7/30	minor spill	5/28
		major fire	0/5	major spill	2/29

Table 5.10: Behavior of Searching Information in Experiment 2: Categories indicate the information given by a decision aid. The numerator of the ratio shows the number of an operator's searches for the corresponding information, and the denominator is the number of the corresponding category detected and noticed by the decision aid. For example, minor fire 4/6 indicates that the subject sought fire 4 times and the decision aid noticed minor fire 6 times.

		SUBJECT A			
no injury	7/9	no fire	1/6	no spill	0/5
possible injury	3/9	minor fire	3/6	minor spill	3/8
		major fire	2/6	major spill	0/5
		SUBJECT B			
no injury	1/10	no fire	0/3	no spill	0/6
possible injury	0/8	minor fire	2/9	minor spill	0/4
		major fire	1/6	major fire	0/8
		SUBJECT C			
no injury	7/7	no fire	0/5	no spill	0/2
possible injury	6/11	minor fire	2/8	minor spill	1/9
		major fire	1/5	major fire	3/7
		SUBJECT D			
no injury	0/9	no fire	0/5	no spill	0/10
possible injury	0/9	minor fire	0/6	minor spill	0/3
		major fire	0/7	major spill	0/5
		SUBJECT E			
no injury	0/11	no fire	0/8	no spill	0/7
possible injury	0/7	minor fire	0/8	minor spill	0/6
		major fire	0/5	major spill	0/5
		TOTAL			
no injury	15/46	no fire	1/27	no spill	0/30
possible injury	9/44	minor fire	6/37	minor spill	4/30
		major fire	4/26	major spill	3/30

Table 5.11: Behavior of Searching Information in Experiment 3: Categories indicate the information given by a decision aid. The numerator of the ratio shows the number of an operator's searches for the corresponding information, and the denominator is the number of the corresponding category detected and noticed by the decision aid. For example, fire 4/6 indicates that the subject sought fire 4 times and the decision aid suggested to search for fire 6 times.

SUBJECT	INJURY	FIRE	SPILL
F	0/0	0/0	0/0
G	0/0	0/0	0/0
H	0/0	0/0	0/0
I	0/0	0/0	0/0
J	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0

Table 5.12: Behavior of Searching Information in Experiment 4: Categories indicate the information given by a decision aid. The numerator of the ratio shows the number of an operator's searches for the corresponding information, and the denominator is the number of the corresponding category detected and noticed by the decision aid. For example, fire 4/6 indicates that the subject sought fire 4 times and the decision aid suggested to search for fire 6 times.

SUBJECT	INJURY	FIRE	SPILL
F	0/0	5/6	3/4
G	0/0	3/5	8/10
H	0/0	5/8	2/5
I	0/0	4/7	4/7
J	0/0	6/8	2/4
TOTAL	0/0	23/34	19/30

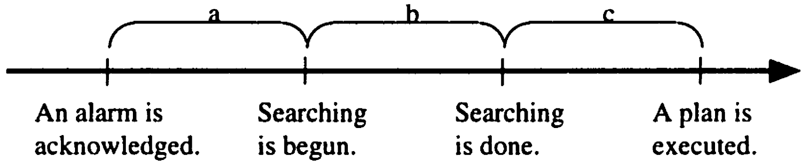

Figure 5-2: Decision Making Time: The decision making time is defined as the sum of the time intervals a and c.

injury, no fire, minor fire, no spill, or minor spill. The number of such searches was 32, compared to 5 for the other situations where there was possible injury, major fire, or major spill. On the other hand, subject C sought 16 times for a corresponding information category when the decision aid said there was no injury, no fire, minor fire, no spill, or minor spill. For the other information given, subject C sought 22 times for the corresponding information.

These results imply that subjects had very different strategies or different ways of searching information though they were trained in a same way. No one tried to search all categories apparently because of the time pressure. Therefore the information category searched was very critical to make a better response plan.

In experiments 3 and 4, each subject was asked to follow strictly the suggestion of the decision aid, except one case. Subjects were asked to dispatch a fire engine without searching when the decision aid suggested for them to search both fire and spill at the same time.

5.3.4 Decision Making Time

The decision making time was defined as the time taken from the moment an alarm is acknowledged on the simulator screen to the moment the subject executed the response plan excluding time for searching information, because the searching time is fixed throughout the experiments and the information was shown at the end of the searching time. In Figure 5-2, the decision making time is the sum of the time interval a and the time interval c.

In Figure 5-3, all collected data (see Appendix G for individual data) for decision making time are plotted in a boxplot[3]. Each column shows the decision-making time of the corresponding experiment.

The average decision making time in experiment 2 was longer than that in experiment 1. The average decision making time in experiment 4 was longer than that in experiment 3. Since the probability of getting correct information through the operator's observation was higher than the

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[3] A boxplot is a box and whisker plot. The box has lines at the lower quartile, median, and upper quartile values. The whiskers are lines extending from each end of the box to show the extent of the rest of the data.

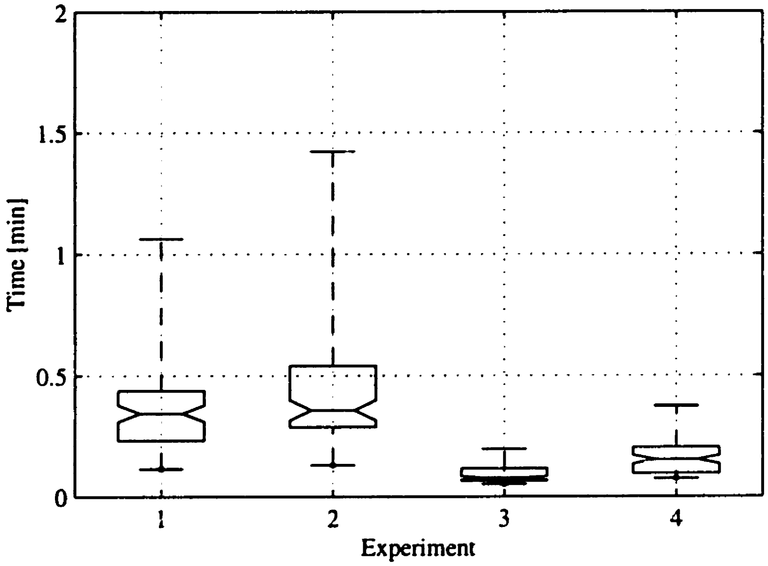


Figure 5-3: Time for Decision Making

Table 5.13: Statistics of Decision Making Time

	EXPERIMENT 1	EXPERIMENT 2	EXPERIMENT 3	EXPERIMENT 4
MEAN (min)	0.3674	0.4398	0.0896	0.1574
VARIANCE	0.0300	0.0579	0.0010	0.0041

Table 5.14: Behavior of Intervention in Experiment 1 and 2: The numerator of the ratio is the number of correct intervention, and the denominator is the number of total intervention. The maximum achievable number of intervention is 90.

SUBJECT	EXPERIMENT 1	EXPERIMENT 2
A	2/8	1/2
B	1/2	0/1
C	0/2	8/10
D	0/0	1/15
E	1/3	0/5
TOTAL	4/15	10/33

Table 5.15: Behavior of Intervention in Experiment 3 and 4: The numerator of the ratio is the number of correct intervention, and the denominator is the number of total intervention. The maximum achievable number of intervention is 90.

SUBJECT	EXPERIMENT 3	EXPERIMENT 4
F	0/0	9/9
G	0/0	13/13
H	0/0	7/8
I	0/0	11/11
J	0/0	10/10
TOTAL	0/0	50/51

probability of the decision aid in experiment 2 and 4 than in experiment 1 and 3, subjects seemed to consider longer whether or not to get additional information and how to estimate the characteristics of an incident when they had additional information. It also seemed that in experiment 1 subjects quickly made a response plan based on the information given by the decision aid, because the quality of expected additional information was poorer than the quality of information shown on the incident management window.

Also, the average decision making times in experiment 3 and 4 are shorter than those in experiment 1 and 2. Since the new human-computer interface directly suggested to subjects what to do, it could shorten the decision making time, compared that the current human-computer interface in experiment 1 and 2 just told what an incident could be.

5.3.5 Intervention

A human intervention could be considered as a subject's decision to modify the plan suggested by the decision aid. There were 90 trials (18 trials times 5 subjects) for each experiment. Table 5.14 summarizes the intervention behavior of each subject in experiment 1 and 2, and Table 5.15

Table 5.16: Performance in Experiment 1 and 2

SUBJECT	EXPERIMENT 1	EXPERIMENT 2
A	6	8
B	10	9
C	7	9
D	10	-1
E	6	5
TOTAL	39	30

Table 5.17: Performance in Experiment 3 and 4

SUBJECT	EXPERIMENT 3	EXPERIMENT 4
F	9	14
G	9	12
H	12	11
I	8	12
J	11	13
TOTAL	49	62

summarizes the intervention behavior in experiment 3 and 4.

The results show that subjects made many unnecessary and wrong interventions in experiment 1 and 2. One reason is that subjects did not make correct estimation of the state when given information was in conflict as shown in Section 5.3.1. In experiment 3, the decision aid never suggested to search information, because, based on the intervention theory, it was futile to search with the given performance level of the operator and given costs. On the other hand, in experiment 4, subjects were suggested what to search and how to change the response plan, which resulted in good performance of intervention.

5.3.6 Performance

For each trial, the performance of a subject's decision making was measured as: if an incident was cleared within a time limit with a correct response plan, +1 point was given. If an incident was cleared within a time limit with a wrong response plan, 0 points were given. If an incident was not cleared within a time limit, −1 point was given.

Table 5.16 and Table 5.17 show the performance points achieved by each subject. The achievable performance points for each experiment were 90 points (18 trials times 5 subjects). The total performance points in experiment 4 were much higher than those in experiment 2, and the total performance points in experiment 3 were higher than those in experiment 1. That implies that the performance with the new proposed interface is better than that with the current interface.

5.4 Summary of Experiments

Throughout the experiments, we observed that subjects did not make correct estimation of states and made different response plans from subject to subject with the current human-computer interface. With the proposed new human-computer interface, it was shown that subjects made a response plan more quickly, consistently, and correctly than with the current interface.

Chapter 6

Conclusions, Contributions, and Suggestions for Further Research

6.1 Conclusions and Contributions

In 1958 Morehouse [29] stated the purpose of human factors engineering or human-machine systems engineering:

> The ultimate aim of each human factors effort is toward the optimal utilization of human and machine capabilities to achieve the highest degree of effectiveness of the total system.

In order to achieve the ultimate goal, various studies have been carried out – how or what a human operator should do, and how or what a human operator actually does. The results show a great discrepancy between what(or how) a human operator should do and what(or how) a human operator actually does. Concluding that a human operator is suboptimal, many such studies recommend building better human-machine systems by building better decision aids. Decision aids, however, often are not successfully utilized and in some applications are totally rejected in spite of the advance of the computer technology and artificial intelligence.

It has been questioned why a decision aid is not used as it is supposed to be. Some research reviewed in Chapter 3 indicated causes due to subjective factors such as insufficient and excessive trust in a decision aid, too much or too little self-confidence by an operator, and mental workload. Though such subjective factors are important, they do not tell how to achieve the ultimate goal - the optimal utilization of human and machine (or computer) capabilities. Here we ignore, the author thinks, the fundamental facts in designing the system. First, any decision aid is not and will not be perfect, because the maker of the decision aid, the human, is not and will not be perfect. We need to acknowledge our limit that we cannot design a perfect decision aid. Second, in some task a human operator, though they are not well educated or trained, perform better than a computer or a machine. In some task, it is not appropriate to say that a human operator is suboptimal or to replace human operators with computers.

Therefore, the main issue to be addressed is how to use an *imperfect* decision aid or how to coordinate a human operator and a decision aid, not how to make a *perfect* decision aid. An operator must be helped to know in a systematic and objective way when and how to accept or to modify a suggestion generated and given by a decision aid.

This dissertation developed a theory of human intervention in human-machine systems and its application to human-computer interfaces. A paradigm of human intervention in supervisory control was presented in order to explain when and how an operator should or should not engage a decision aid, initiate automatic control, or allow automatic control to be completed. A prescriptive model of human intervention in supervisory control was developed in the context of traffic incident management and based on probabilistic descriptions about the performance of a decision aid. the performance of an operator, and costs for consequences of each decision. The model provides a decision rule regarding how to use a decision aid for when to intervene and how to override a decision aid under time pressure: (1) to dispatch agents immediately, (2) to not take any action and ignore the current event, or (3) to look for further confirming or disconfirming information and decide later.

The model provided a conceptual basis for a new human-computer interface to give operators more refined advice for various alternative actions than is now given in the current Central Artery/Tunnel interface. In contrast to the current interface, which emphasizes the states of an incident which themselves are uncertain, the new interface suggests to the operator an action along with a degree of certainty.

Through human-in-the-loop experiments with an incident management simulator, the new design was shown not only to eliminate unnecessary human intervention. but also to guarantee human intervention as necessary, which results in the improvement of overall performance of incident management compared to performance with the current interface. Also, since the new interface directly suggests to operators what to do, it shortens the decision time significantly compared to the current interface.

The most significant characteristics of the interface developed based on the intervention model are summarized as follows:

- It can be built on an existing decision aid. The data needed for the intervention model are the performance levels of a decision aid and a human operator. and the costs of consequences of decisions. The performance level of a decision aid (p_{ij}, conditional probabilities that the decision aid detects the state is i when the true state is j), the performance level of an operator (q_{ij}, conditional probabilities that the operator detects the state is i when the true state is j) can be obtained by various reliability and performance tests. Once having these data, we can derive the intervention rule and apply it to redesign a human-computer interface upon on the existing decision aid.

- It presents to an operator a recommendation regarding how to use a decision aid rather than giving ambiguous information. It states to an operator whether to accept or to ignore the decision aid. A decision aid must give an operator advice to ignore the decision generated by the decision aid, whenever appropriate.

- It provides an estimate of error. The estimate tells an operator the consequence of a decision and helps build trust in the decision aid.

- By using both the decision aid and the human operator effectively and efficiently, we can fully utilize a decision aid and maximize the performance of a human-machine system.

6.2 Suggestions for Further Research

Implementation in the CA/T system

The model of intervention was applied to a small-scale incident management simulator with naive subjects (MIT students). Because of their background and education, experimental subjects had more familiarity of the usage of computers than average persons. Their familiarity with the computer and their quick learning made them represent experienced operators in some sense. Nevertheless, for further verification, it may be desirable to carry out a field study with "real" operators in the "real" incident management of the CA/T project.

Extension to other supervisory control systems

This study is focused on how to use an existing decision aid and how to coordinate human operators with that decision aid. The intervention theory provides not only guidance in designing decision support systems, operational procedures, and operator training, but also helps to achieve optimal performance of the human-machine system. The theory in this work can be applied in other contexts, such as power plants, process control, high-speed trains [2], commercial aviation [34], and telesurgery [45].

Modeling of supervisory control

Three theories were used to develop the intervention model: decision analysis, dynamic programming, and finite state machines. Decision analysis is a tool to find a decision which maximizes an expected value of utility functions. Dynamic programming is for an optimization of an objective function with a temporal course of actions or decisions. Finite state machine theory provides a framework of describing a system which changes its state at discrete times according to its inputs and outputs.

As the supervisor's role is shifted from continuous manual control to making decisions at discrete times, the modeling of a supervisor is focused on modeling of decision making at discrete times. Since decisions are made to maximize an objective function (or to minimize a cost function) at discrete times, the combination of these theories can be used to model other human operator's roles in supervisory control or to model a supervisory control system.

References

[1] Arthur D. Little, Inc. *Cost-Effectiveness in Traffic Safety.* Frederick A. Praeger, New York, NY, 1968.

[2] Shumei Y. Askey. *Design and Evaluation of Decision Aids for Control of High-Speed Trains: Experiments and Model.* PhD thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1995.

[3] D. Berg, B. Legg, and L. Showalter. Seattle area incident management program. *ITE journal*, pages 265–269, 1992.

[4] Dimitri P. Bertsekas. *Dynamic Programming and Optimal Control*, volume 1. Athena Scientific, Belmont, MA, 1995.

[5] Edward H. Blum. The New York city fire project. In Alvin W. Drake, Ralph L. Keeney, and Philip M. Morse, editors, *Analysis of Public Systems*, chapter 7, pages 94–132. MIT Press, Cambridge, MA, 1972.

[6] R.W. Brindley. Incident management for the Central Artery/Tunnel project. Bechtel/Parsons Brincherhoff, Boston, MA, August 1991.

[7] Robert T. Clemen. *Making Hard Decisions: An Introduction to Decision Analysis.* Duxbury Press, Belmont, CA, 1990.

[8] Alvin W. Drake and Ralph L. Keeney. *Decision Analysis.* Massachusetts Institute of Technology, Center for Advanced Engineering Study, Cambridge, MA, 1986.

[9] Anne Edland and Ola Svenson. Judgment and decision making under time pressure: Studies and findings. In Ola Svenson and A. John Maule, editors, *Time Pressure and Stress in Human Judgment and Decision Making*, chapter 2, pages 27–40. Plenum Press, New York, NY, 1993.

[10] Gene F. Franklin, J. David Powell, and Abbas Emami-Naeini. *Feedback Control of Dynamic Systems.* Addison-Wesley Publishing Company, Reading, MA, 1986.

[11] E. Hollnagel. *AI + HCI: Much ado about nothing?* Computer Resources International, Copenhagen, 1989.

[12] Shulamit Kahn. Economic estimates of the value of life. *IEEE Technology and Society Magazine*, pages 24–31, June 1986.

[13] D. Kahneman, P. Slovic, and A. Tversky. *Judgment Under Uncertainty: Heuristics And Biases.* Cambridge University Press, Cambrdige, MA, 1982.

[14] Ralph L. Keeney and Howard Raiffa. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs.* Cambridge University Press, Cambridge, UK, 1993.

[15] Suyeong Kim. IPCS Design Refinements for the Central Artery/Tunnel. Technical Report Technical Service Contract 93182-T-266, Massachusetts Institute of Technology, Department of Mechanical Engineering, Cambridge, MA, September 1993.

[16] Suyeong Kim. Tutorial for experimental subjects for the Central Artery/Tunnel project. Technical report, Massachusetts Institute of Technology, Human-Machine Systems Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technolgoy, Cambridge, MA, May 1996.

[17] Suyeong Kim and Thomas B. Sheridan. Human intervention into automatic decision-making and automatic control. In *The 6th IFAC Symposium on Analysis, Design, and Evaluation of Man-Machine Systems*, pages 133–139, Cambridge, MA, June 1995.

[18] Alex Kirlik. Modeling strategic behavior in human-automation interaction: Why an "aid" can (and should) go unused. *Human Factor*, 35:221–242, 1993.

[19] Gary A. Klein and Roberta Calderwood. Decision models: Some lessons from the field. *IEEE Transactions on Systems, Man, and Cybernetics*, 21(5):1018–1026, 1991.

[20] Richard C. Larson. *Urban Police Patrol Analysis*. MIT Press, Cambridge, MA, 1972.

[21] John D. Lee and Neville Moray. Trust, control strategies and allocation of function in human-machine systems. *Ergonomics*, 35:1243–1270, 1992.

[22] John D. Lee and Neville Moray. Trust, self-confidence, and operator's adaptation to automation. *International Journal of Human-Computer Studies*, 40:153–184, 1994.

[23] Kneale T. Marshall and Robert M. Oliver. *Decision Making and Forecasting: With Emphasis on Model Building and Policy Analysis*. McGraw-Hill, Inc., New York, NY, 1995.

[24] A. John Maule and Ola Svenson. Theoretical and empirical approaches to behavioral decision making and their relation to time constraints. In Ola Svenson and A. John Maule, editors, *Time Pressure and Stress in Human Judgment and Decision Making*, chapter 1, pages 3–25. Plenum Press, New York, NY, 1993.

[25] Jamie McCornack, Lngemar Ragnemalm, and Paul Celestin. *Tricks of the Mac Game Programming Gurus*. Hayden Books, Indianapolis, IN, 1995.

[26] Jonathan D. McDade. Freeway service patrols: A versatile incident management tool. *ITE 1990 Compendium of Technical Papers*, pages 120–124, 1990.

[27] Rebecca C. Milam. Task analysis and operating procedure design for a traffic management system: Application to Boston's Central Artery/Tunnel. Master's thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, June 1994.

[28] Michael J. Moore and W. Kip Viscusi. Doubling the estimated value of life: results using new occupational fatality data. *Journal of Policy Analysis and Management*, 7:476–490, 1988.

[29] L.E. Morehouse. A human factor philosophy. *Human Factors*, 1(1), 1958.

[30] Bonnie M. Muir. Trust between humans and machines, and the design of decision aids. *International Journal of Man-Machine Studies*, 27:527–539, 1987.

[31] Bonnie M. Muir. Trust in automation: Part I. Theoritical issues in the study of trust and human intervention in automated systems. *Ergonomics*, 37(11):1905–1922, 1994.

[32] L.G. Neudorff and J. Dovel. A freeway surveillance and control system for Dade county, Florida. *ITE journal*, pages 125–130, 1990.

[33] Institute of Transportation Engineers. *Transportation and Traffic Engineering Handbook*. Prentice-Hall, Inc., Englewood Cliffs, NJ, second edition, 1982.

[34] Nicolas Patrick. *Decision-Aiding and Optimization for Vertical Navigation of Long-Haul Aircraft*. PhD thesis, Department of Mechanical Engineering, Massachusetts Institute of Technoogy, Cambridge, MA, 1996.

[35] H.J. Payne. FREFLO - a macroscopic simulation model of freeway traffic. *Transportation Research Record*, 722:68–75, 1979.

[36] Richard W. Pew. Human factor issues in expert systems. In M. Helander, editor, *Handbook of Human-Computer Interaction*, chapter 43, pages 931–940. Elsevier Science Publishers B.V., North-Holland, 1988.

[37] E.C. Poulton. *Tracking Skill and Manual Control*. Academic Press, New York, NY, 1974.

[38] Victor A. Riley. *Human Use of Automation*. PhD thesis, University of Minnesota, 1994.

[39] Stephen G. Ritchie and Neil A. Prosser. Real-time expert system approach to freeway incident management. *Transportation Research Record*, 1320:7–16, 1991.

[40] Paul Ross. Some properties of macroscopic traffic models. *Transportation Research Record*, 1194, 1986.

[41] Paul Ross and David Gibson. Survey of models for simulating traffic. *An Overview of Simulation in Highway Transportation*, 7:39–48, 1977.

[42] William B. Rouse. Human-computer interaction in multitask situations. *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-7:384–392, 1977.

[43] Mark S. Sanders and Ernest J. McCormick. *Human Factors in Engineering and Design*. McGraw-Hill, Inc., New York, NY, seventh edition, 1993.

[44] Thomas B. Sheridan. *Telerobotics, Automation, and Human Supervisory Control*. MIT Press, Cambridge, MA, 1992.

[45] Thomas B. Sheridan, Mark Ottensmeyer, and Suyeong Kim. Human-computer cooperation and intervention in telesurgery. *Robotics and Autonomous Systems*, 18:127–134, 1996.

[46] Nancy Staggers and A.F. Norcio. Mental models: concepts for human-computer interaction research. *International Journal of Man-Machine Studies*, 38:587–605, 1993.

[47] Keith A. Stevenson. Emergency ambulance transportation. In Alvin W. Drake, Ralph L. Keeney, and Philip M. Morse, editors, *Analysis of Public Systems*, chapter 8, pages 133–150. MIT Press, Cambridge, MA, 1972.

[48] Dan P. Sydow. *Foundations of Mac Programming*. IDG Books Worldwide, Inc., Foster City, CA, 1995.

[49] The Commonwealth of Massachusetts Highway Department. Central Artery/Tunnel Project. Integrated Project Control System: Summary Description for the Integrated Project Control System. Technical Report CA/T Package No. C22A1, Boston, MA, January 1994.

[50] The Commonwealth of Massachusetts Highway Department. Central Artery/Tunnel Project. Integrated Project Control System: System Design Document. Technical Report CA/T Package No. C22A1, Boston, MA, January 1994.

[51] The Commonwealth of Massachusetts Highway Department. Central Artery/Tunnel Project. Integrated Project Control System: Software Requirements Specification for Central Computer System. Technical Report CA/T Package No. C22A1, Boston, MA, January 1994.

[52] The Commonwealth of Massachusetts Highway Department. Central Artery/Tunnel Project. Integrated Project Control System: Software Requirements Specification for Central Computer System, Appendices A, B and C. Technical Report CA/T Package No. C22A1, Boston, MA, January 1994.

[53] The Commonwealth of Massachusetts Highway Department. Central Artery/Tunnel Project. Integrated Project Control System: Software Requirements Specification for Operator's Console Workstation. Technical Report CA/T Package No. C22A1, Boston, MA, January 1994.

[54] Amos Tversky and Daniel Kahneman. Rational choice and the framing of decisions. In David E. Bell, Howard Raiffa, and Amos Tversky, editors, *Decision Making*, chapter 9, pages 167–192. Cambridge University Press, Cambridge, UK, 1988.

[55] H.B. Wall, B.G. Marsden, and T.A. Parlante. Status of ADOT advanced traffic management system. *ITE journal*, pages 270–274, 1992.

[56] Robert C. Williges, Beverly H. Williges, and Robert G. Fainter. Software interfaces for aviation systems. In Earl L. Wiener and David G. Nagel, editors, *Human Factors in Aviation*, chapter 14, pages 463–493. Academic Press, Sandiego, CA, 1983.

Appendix A

Incident Management Simulator

A.1 Objectives

In the process of designing the Central Artery/Tunnel many questions related to human factors arose, including how to present operating procedures, how to coordinate human operators and computers, how to design displays and controls and workstations, how to reduce human errors and workload, and how to train operators. Most of these questions are well known to the human factors engineering community and are already answered in some applications. However, answers to these questions for the CA/T project cannot be deduced by comparison to other applications' answers, because the CA/T project is quite a new transportation facility, namely an underground highway, and no existing traffic control center in the world can be used as an accurate model. In order to answer these important questions at the early design stage and to suggest a design guide, the incident management simulator was built.

The incident management simulator simulates interactions between a human operator at the OCC and the IPCS under various situations, and enables one to investigate how a human operator makes a decision. It measures what operators' responses are and how long they take. The time distribution data of operators' responses to various incidents gives us a basis to decide whether or not the overall estimated time for incident clearance is fit for the design specifications. A human operator's responses can be used to verify whether human operators and the IPCS are well matched, or how a procedure for the CA/T incident management can be improved to meet the design goal.

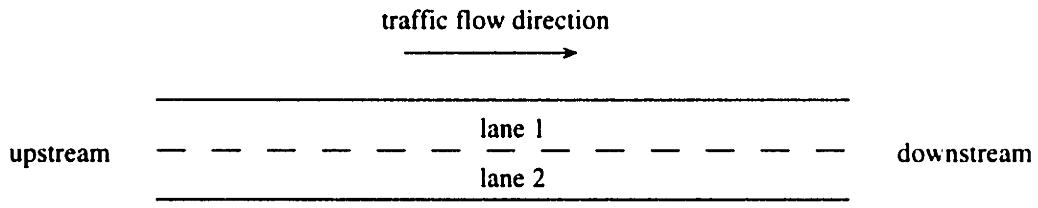


Figure A-1: Upstream, Downstream, and Lanes

A.2 Development Tools

The development platform for the simulator is a Macintosh (TM) computer with MacOS (TM) version 7.1 or above. The programming language is ANSI C++ with Macintosh Toolbox library [48]. Metrowerk CodeWarrior (TM) is used as a compiler.

A.3 Terminology and Notation

The highway considered in the simulator is the east bound Ted Williams tunnel. It is a two lane tunnel under the Boston harbor. The lane 1 is the left lane and the lane 2 is the right lane. The traffic goes from left to right as shown in Figure A-1. The tunnel is divided into 20 sections along the length. Each section is 100 feet long.

Traffic density is the number of vehicles per unit length of the road and its unit is vehicles per mile. Traffic volume is the number of vehicles passing through a point of road per unit time. The unit for the traffic volume is vehicles per hour.

An incident can be defined as an event that causes an abnormal traffic flow pattern inside tunnel, and be characterized by the location, the lane(s) blocked, the number of vehicles involved, the existence of personal injury, the existence of fire, and the existence of hazardous material spill.

The available agents are emergency response teams (ERT), the Massachusetts state police (MSP), the Boston fire department (BFD), and emergency medical services (EMS). They can approach an incident location from upstream or from downstream. The approach from downstream is called *reverse approach.*

A.4 Simulator Structure

In order to represent the environment of the human operators at the OCC, the incident management simulator needs to describe the traffic, the incident, the agents, the sensors, and the IPCS.

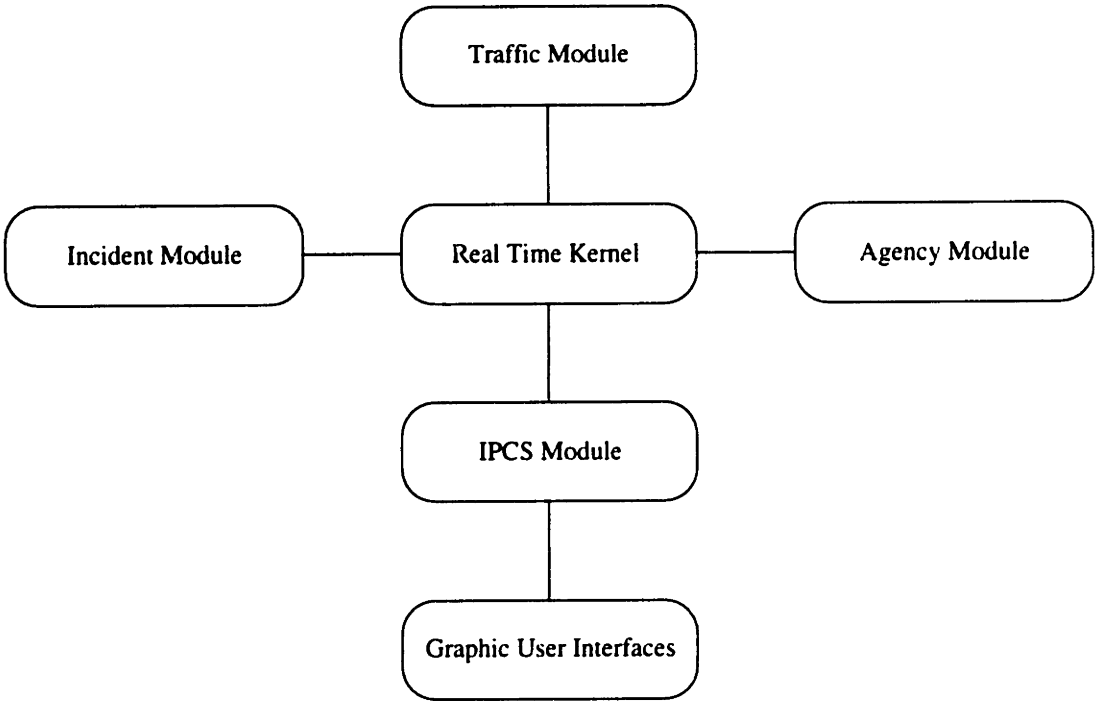


Figure A-2: Structure of Incident Management Simulator

The simulator has a module corresponding to each element of the environment: the traffic module, the incident module, the agent module, the graphic user interface module, and the IPCS module, as shown in Figure A-2.

In order to observe the *real-time* human-computer interaction, the simulator needs to operate in real time. A *polling* method was selected to be real time, and has a time-checking routine so that it makes the simulator idle until the next time step. It is easy to implement and the timing is accurate enough for the simulator [25]. In the simulator, all variables are updated every one second.

A.4.1 Modeling of an Incident

An incident can be characterized by:

1. the location: the section where an incident happens,
2. the lane(s) blocked: the left lane, the right lane, or both lanes,
3. the number of vehicles involved: 0, 1, 2, or more than 3 vehicles,
4. the existence of personal injury: no injury or possible injury,
5. the existence of fire: no fire, minor fire, or major fire,

6. the existence of hazardous material spill: no spill, minor spill, or major spill.

The location is one of the sections in the tunnel. The number of vehicles involved in an incident can be any number, but is limited to zero, one, two, or three for simplicity. Since there are only two lanes, the left lane, the right lane, or both lanes can be blocked. The existence of personal injury can be no injury or possible injury. The existence of fire means no fire, minor fire, or major fire. A minor fire is a fire which can be managed by an emergency response team (ERT) alone. On the other hand, a major fire needs fire fighters (BFD) and prevents vehicles from passing near the fire. A hazardous material spill can be a toxic liquid, a toxic gas, or anything which impedes the traffic flow. It can be no spill, minor spill, or major spill. A minor spill can be handled by ERT, a major spill should be handled by the BFD. A major spill also prevents vehicles from passing by.

Since an incident is a dynamic process, an incident can change its characteristics as time passes. For example, a minor fire can escalate to a major fire, and a minor spill can become a major spill. The probability of transition determines the behavior of transition.

A.4.2 Highway and Traffic Control Devices

The simulator considers only the Ted Williams Tunnel east bound, which has two lanes. The tunnel is divided into 20 sections along the traffic flow. The most upstream section is labeled as section 1, and the most downstream section is section 20. Each section is 400 feet long.

Traffic control devices considered are lane use signs (LUS), variable speed limit signs (VSLS), and variable message signs (VMS). An LUS is for indicating whether or not this lane is open to the public by showing a green arrow, a yellow cross, or a red cross. A VSLS is for regulating the upper limit of a vehicle's speed. A VMS is a text message which gives information to the public. The size of each device is limited by the size of the tunnel. In the Ted Williams Tunnel, an LUS is 12 inches by 12 inches, a VSLS is 8.5 inches by 12 inches, and a VMS is one line of 12 characters 8.6 inches by 12 inches. Table A.1 shows where a traffic control device is installed for each road section.

A.4.3 Modeling of Traffic Flow

Macroscopic Traffic Flow Model

There are many models which describe the dynamic behavior of traffic flow. Traffic flow can be described like a fluid moving through a pipe, or each vehicle can be modeled by how it accelerates and how it changes the lane. The former model is called a macroscopic traffic flow model, and the latter is called a microscopic traffic flow model [33, 41].

Table A.1: Installed Traffic Control Devices ($\surd$: installed, –: not installed)

SECTION	LUS	VMS	VSLS
1	√	–	√
2	√	√	–
3	√	–	–
4	√	√	–
5	√	–	–
6	√	√	–
7	√	√	–
8	√	–	√
9	√	–	–
10	√	√	–
11	√	–	–
12	√	√	–
13	√	–	√
14	√	√	–
15	√	–	–
16	√	√	–
17	√	–	–
18	√	√	–
19	√	–	√
20	√	√	–

A microscopic model is based on two components of driving of vehicles, namely the so called car-following behavior and the lane-changing behavior. While this model can show the details of traffic flow, it needs a lot of effort in computation.

A macroscopic traffic flow model represents the traffic flow based on the average traffic speed, the average traffic density, and the average traffic volume of each road section, but is not based on each vehicle. In a macroscopic model, the traffic flow is assumed continuous and there is a hypothetical relationship between the traffic speed and the traffic density. This model also has been used in many commercial traffic simulation packages such as FREFLO[35], KRONOS, and RFLO[40].

The major three variables of the macroscopic traffic modeling are the traffic volume q [the number of vehicles per hour], the traffic density d [the number of vehicles per mile] and the average traffic speed v [miles per hour]. Among many models, the simplest deterministic traffic flow model can be described as follows [40]:

$$q = kd \tag{A.1}$$

$$\frac{\partial d}{\partial t} = -\frac{\partial q}{\partial x} + S(x,t) \tag{A.2}$$

$$v = v_f\left(1 - \frac{d}{d_{jam}}\right) \tag{A.3}$$

where S is source strength of vehicles for each section, v_f is the free flow speed, d_{jam} is the jam density. The first equation is the definition of traffic volume, and the second equation is from the assumption of the continuity of traffic flow. The last equation is based on a hypothesis regarding traffic flow velocity and traffic flow density.

Discrete Traffic Flow Model

By using the simple Euler formula, we can derive the following discrete time equations from the continuous time equations. Let's denote that d_{ij}^k, v_{ij}^k, and q_{ij}^k are the density, the velocity, and the volume of section i and lane j at time step k, respectively. s_{ij}^k is the traffic volume moving from section i and lane j to section $i+1$ and lane j at time step k. r_{ij}^k is the traffic volume moving from section i and lane j to section i and the next lane $\bar{j}$ at time step k.

$$\begin{aligned} d_{ij}^{k+1} &= d_{ij}^k + \frac{\Delta t}{\Delta l}\left(s_{i-1,j}^k - s_{ij}^k + r_{i\bar{j}}^k - r_{ij}^k\right) && \text{(A.4)} \\ v_{ij}^{k+1} &= v_f\left(1 - \frac{d_{ij}^k}{d_{jam}}\right) && \text{(A.5)} \\ q_{ij}^{k+1} &= d_{ij}^k v_{ij}^k && \text{(A.6)} \end{aligned}$$

where Δt is the size of time step and ΔL is the length of section.

The traffic flow from upstream to downstream or from lane to lane is affected by an incident, an LUS, a VMS, or a VSLS.

$$s_{ij}^k = \begin{cases} 0 & \text{if there is an incident at section } i\text{, lane } j \\ d_{ij}^k v_{i+1,j}^k (1-\alpha) & \text{if LUS is not a green arrow} \\ d_{ij}^k v_{i+1,j}^k & \text{otherwise} \end{cases} \qquad \text{(A.7)}$$

$$r_{ij}^k = \begin{cases} d_{ij}^k v_{i\bar{j}}^k \beta & \text{if there is an incident at section } i\text{, lane } j \\ d_{ij}^k v_{i\bar{j}}^k \alpha\gamma & \text{if LUS is not a green arrow} \\ (d_{i\bar{j}}^k - d_{ij}^k) v_{i\bar{j}}^k \delta & \text{otherwise} \end{cases} \qquad \text{(A.8)}$$

The parameters, v_f and α, are assumed to depend on the message of traffic control devices and the incident. v_f depends on a VSLS and is assigned 5 MPH more than the message of a VSLS. α can be considered to represent how drivers follow the LUS and depends on the VMS. β, γ, and δ are the rates of lane changing.

Table A.2: Agent Speed with Traffic Flow Volume

TRAFFIC FLOW VOLUME (VPH)	AGENT SPEED (MPH)
light (0 - 800)	30 - 50
medium (800 - 1600)	20 - 35
heavy (1600 -)	10 - 20

Table A.3: Effort Needed to Clear an Incident

CHARACTERISTICS	UNIT EFFORT
vehicle	350 per vehicle
injury	500
fire	600 for minor, 1200 for major
spill	600 for minor, 1200 for major

A.4.4 Modeling of Agents

Four agents are considered in the simulator: emergency response teams (ERT), Massachusetts state police (MSP), Boston Fire Department (BFD), and emergency medical services (EMS). The dynamics of agents considered in the simulator are the spatial movement in the tunnel and the activity of clearing an incident.

Also the moving speed of such an agent is dependent on the traffic volume. If the traffic flow is heavy, then an agent moves slowly. If the traffic flow is light, an agent moves fast. Based on the traffic pattern, the traveling speed of an agent is assigned at each time step (see Table A.2). The spatial movement or the distance traveled is calculated based on the speed.

After arriving at an incident location, an agent starts to clear an incident. Each agent has its own specialty and some limited ability. ERT is to remove disabled vehicles, to extinguish a minor fire, and to clear a minor spill. It is needed for every incident. MSP is needed to if there are more than two vehicles, possible injury, a fire, and/or a spill. BFD clears a fire and a spill. EMS is needed for injured persons and for a major fire or spill.

Times for clearing an incident for each agency are also dependent on the severity of an incident.

Table A.4: Agent's Ability to Clear an Incident per Unit Time (1 second)

AGENCY	VEHICLE	INJURY	FIRE	SPILL
ERT	1	0	0	0
MSP	0.2	0.2	0	0
EMS	0	1	0.1	0.1
BFD	0	0	1	1

The ability and the effort to clear an incident are assigned as relative numbers as shown in Table A.3 and A.4. For example, if one vehicle breaks down and an ERT is dispatched, it will take about 6 minutes to clear the vehicle.

If there is no more effort for an agency to clear, then the agency returns to its station after notifying an OCC operator. However, an MSP will remain at the end of a clearing activity and leaves the incident location when the incident is totally cleared.

A.4.5 Modeling of the IPCS

The IPCS module is responsible for generating an alarm, conducting an incident management dialog, making a response plan, and executing the plan. In the simulator, the alarm is automatically generated as soon as the simulation starts. An incident management dialog box shows as soon as an operator accepts the alarm. The incident management dialog delivers incident information which is detected by various sensors. The information shown on the incident management dialog box can be wrong or correct, which depends on each incident scenario.

A response plan consists of three components: which agencies to be dispatched, how to close the tunnel (partially or fully), and how for an agency to approach the incident location (from upstream or from downstream). The IPCS generates a plan based on the collected information by a set of predefined rules .

Agency Approach

In most situations, agents approach the incident location from upstream, except in the following cases:

1. when both lanes are blocked by the incident, or
2. when traffic is heavy and the incident location is closer to the tunnel exit than the tunnel entrance

Tunnel Closure

The tunnel should remain open to the public as much as possible unless the safety of the public is endangered. The tunnel should be fully closed when there is a major fire or a major spill, or both lanes are blocked.

Agents

In this experiment, agents needed for an incident obey the following rules:

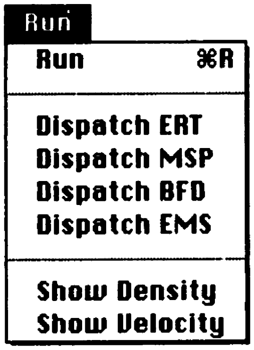


Figure A-3: Run Menu Bar and Sub Items

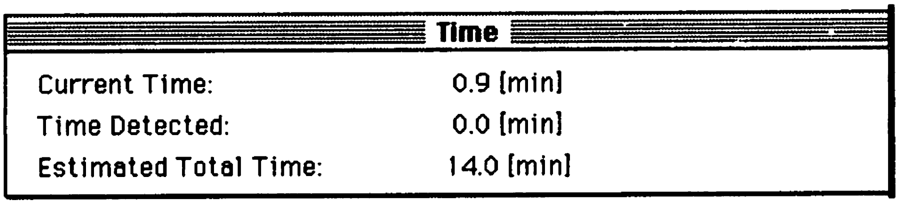
- If there is only one vehicle without injury, dispatch ERT.
- If there is more than one vehicle, dispatch ERT and MSP.
- If there is a possible injury, dispatch ERT, MSP, and EMS.
- If there is a minor fire or a minor spill, dispatch ERT and MSP.
- If there is a minor fire or a minor spill with a possible injury, dispatch ERT, MSP, and EMS.
- If there is a major fire or a major spill, dispatch ERT, MSP, and BFD.
- If there is a major fire or a major spill with a possible injury, dispatch ERT, MSP, BFD, and EMS.

A.4.6 Graphic User Interfaces

Menu Bar

The menu bar shows three menu items, *File*, *Edit*, and *Run*. A subject will use only the *Run* menu item.

The *Run* menu has seven items, *Run*, *Dispatch* ERT, *Dispatch* MSP, *Dispatch* BFD, *Dispatch* EMS, *Show Density*, and *Show Velocity* as shown in Figure A-3. The *Run* item is to run the simulator and to open a file open dialog if an incident scenario is not loaded. The *Dispatch* ERT item, the *Dispatch* MSP item, the *Dispatch* BFD item, and the *Dispatch* EMS item are used when an operator wants to dispatch an agent, which opens a dispatch dialog (Figure A-8). *Show Density* and *Show Velocity* set the traffic window display to the traffic density and the traffic velocity, respectively.



Current Time: 0.9 [min]
Time Detected: 0.0 [min]
Estimated Total Time: 14.0 [min]

Figure A-4: Time Window

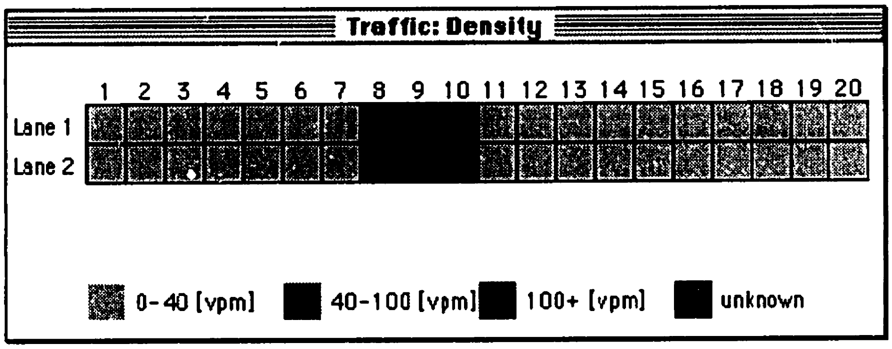


Figure A-5: Traffic Window

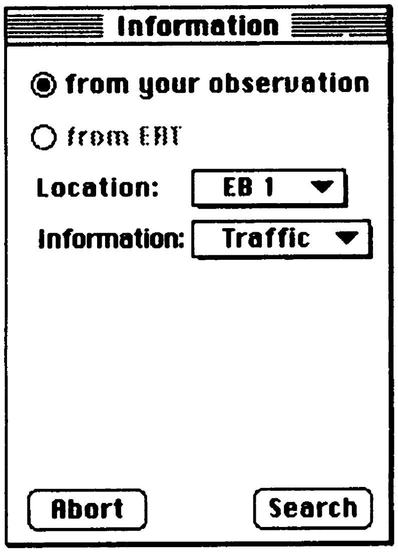
Windows

As soon as an incident scenario is executed, three windows are shown on the screen: a *time* window, a *traffic* window, and an *information* window.

The time window shows three clocks (Figure A-4). *Current Time* is the time elapsed since an experiment starts. *Time Detected* is the time when an incident is detected. *Estimated Total Time* is the estimated time duration to clear the detected incident based on information collected by an operator. If information is not obtained by an operator, then the simulator estimates the time based on the worst possible incident and the given response plan.

The traffic window shows the traffic information for each section and lane of the road (Figure A-5). The traffic flow moves from left to right. The top row is the left lane and the bottom row is the right lane. Each rectangle represents a road section. The left most is the beginning of the tunnel and the right most is the end of tunnel. A corresponding section number is shown on the top of each section.

The title of the traffic window indicates what traffic variable is shown. For the traffic velocity, light gray means that the average traffic speed is more than 35 miles per hour (MPH). Gray says that the average traffic speed is between 35 MPH and 15 MPH. When the average traffic speed is lower



● from your observation

○ from ERT

Location: EB 1

Information: Traffic

Figure A-6: Information Window

than 15 MPH, the color turns to dark gray. If a sensor in a section breaks down and no information is available, it will be black.

An operator can find the traffic information of a specific location by double-clicking that location with the mouse. The details of traffic information are shown in terms of volume (vehicles per hour), velocity (miles per hour), and density (vehicles per mile).

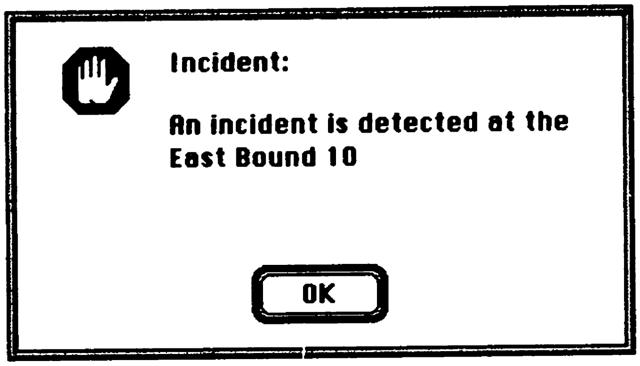
The information window delivers what information an operator can get during incident management (Figure A-6). In order to get information, an operator selects the information source, location, information type, and clicks the search button. Information source is *from your observation* or *from* ERT. *From* ERT is only available after ERT is arrived at the location.

There are six categories of information such as: a traffic pattern, blocked lanes, number of vehicles, injury, fire, and spill. When an operator clicks the search button, it takes time to get information, which reflects the time consumed in the actual incident management.

Dialogs

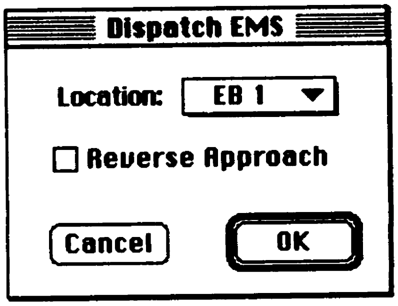
As soon as the simulator starts, an alarm dialog box pops up on the screen while freezing all other user interfaces. An alarm dialog box shows the possible incident location. The dialog box disappears when an operator clicks the OK button.

If an operator wants to dispatch agents other than those already dispatched, a dispatch dialog (Figure A-8) can be opened by using an item under the *Run* menu. An operator needs to choose a


Incident:

An incident is detected at the East Bound 10

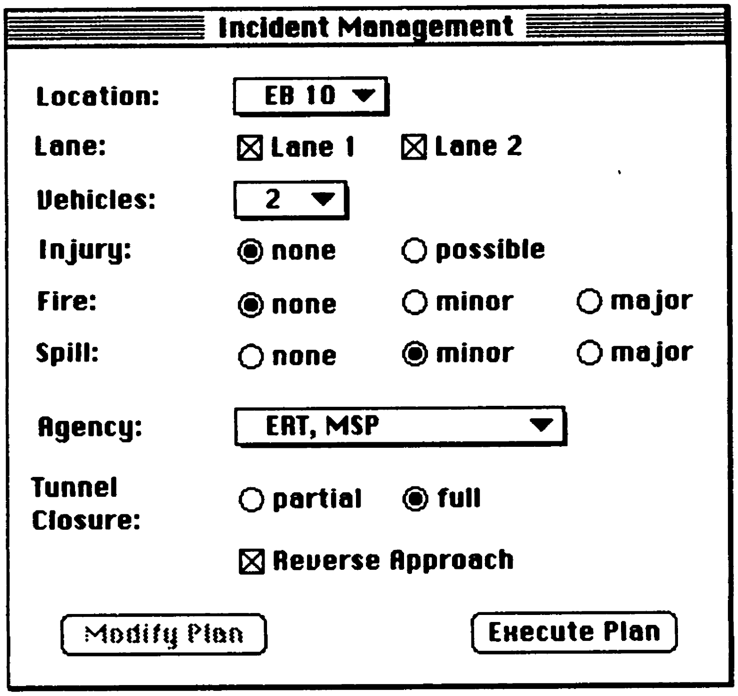
Figure A-7: Alarm Dialog Box



Location: EB 1

☐ Reverse Approach

Figure A-8: Dispatch Dialog Box



Location: EB 10
Lane: ☒ Lane 1 ☒ Lane 2
Vehicles: 2
Injury: ● none ○ possible
Fire: ● none ○ minor ○ major
Spill: ○ none ● minor ○ major
Agency: ERT, MSP
Tunnel Closure: ○ partial ● full
☒ Reverse Approach

Figure A-9: Incident Management Dialog Box A: Based on the Current Design Document

location and the way to approach the location.

A.4.7 Incident Management Dialog

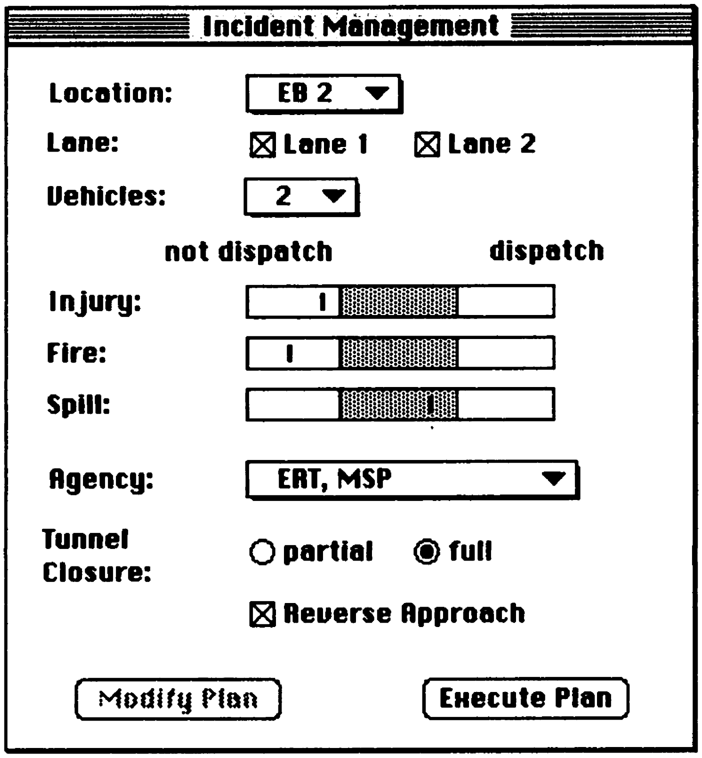
As soon as an alarm is accepted, either an incident management dialog box A or B pops up on a computer screen and shows the detected characteristics of the incident and a computer-recommended response plan.

Incident Management Dialog A

An incident management dialog A shows the states of incident characteristics. It provides an operator the existence of each incident characteristics such as an injured person, fire, or hazardous material spoilage.

In order to modify a plan, an operator can change one of incident characteristics and then click the *Modify Plan* button or change the plan directly. When the *Execute Plan* button is clicked, all elements of the plan are automatically executed.

Incident Management Dialog B



Location: EB 2

Lane: ☒ Lane 1 ☒ Lane 2

Vehicles: 2

Injury:

Fire:

Spill:

Agency: ERT, MSP

Tunnel Closure: ○ partial ● full

☒ Reverse Approach

Figure A-10: New Incident Management Dialog Box B: Based on the Human Intervention Model

An incident management dialog B suggests the actions of an operator. For each incident's characteristics, it suggests whether to dispatch a corresponding agent, to search additional information about it, or not to dispatch a corresponding agent.

In order to modify a plan, after searching additional information, an operator can click the *Agency* pull-down menu and select one of desirable agents, and then click the *Execute Plan* button.

A.4.8 Uncertainties

Various uncertainties are added to the simulator. They can be made to different from one incident scenario to another. Uncertainties can be added in collecting information through the information window and in pre-classified incident information in the incident management window.

It is assumed that every sensor is not perfect or there may be a difficulty to interpret a visual screen because it is corrupted by smoke or whatever. Therefore the information collected from the sensors may be corrupted or erroneous. However the information from the ERT is assumed always correct, because it is at the location and the ERT is trained well enough not to make such a mistake.

Since the IPCS gets information only from sensors and the information from sensors can be corrupted, it is assumed that the IPCS can generate wrong decisions or information. But it is assumed that the IPCS never fails to carry out any given commands from an operator. Therefore the information or the decision on an incident management dialog may be erroneous. but the IPCS executes exactly what it is asked to do.

The traffic information on the traffic window is assumed accurate if the information is available.

Appendix B

On Decision Analysis

This appendix reviews the basics of the decision analysis – the probability and the utility [7, 14, 23].

B.1 Definitions

B.1.1 Lottery

A *lottery* is a probabilistic trial, characterized by a mutually exclusive, collectively exhaustive set of possible outcomes, $C_1, C_2, \ldots, C_m$, with respective probabilities $p_1, p_2, \ldots, p_m$. We denote lotteries as $L(C_1, \ldots, C_m; p_1, \ldots, p_m)$. For example, $L(\$5, \$0; 0.6, 0.4)$ indicates a lottery with probability 0.6 of a \$5 payoff and probability 0.6 of \$0 payoff.

B.1.2 Preference

We assume that a decision maker always has preferences among possible consequences. In other words, for every pair of consequences C_i and C_j, a decision maker will either prefer C_i to C_j, be indifferent between C_i and C_j, or prefer C_j to C_i.

$C_i \succ C_j$ C_i is preferred to C_j.

$C_i \sim C_j$ C_i and C_j are equally preferred.

$C_i \succeq C_j$ C_i is either preferred to or as preferred as C_j.

Also assume that for a set of consequences $C_1, \ldots, C_m$, there are two particular consequences C^* and C_*. C^* is a consequence which is at least as preferred as the most preferred of $C_1, \ldots, C_m$, and C_* is a a consequence which is at least as low in preference as the least preferred of $C_1, \ldots, C_m$. Note that C^* and C_* do not need to belong to $C_1, \ldots, C_m$.

B.2 Probability: Representation of Uncertainty

B.2.1 Different Perspectives

The traditional way of modeling uncertainties is using probability. But the concept of probability seems to be used differently in different contexts. Here the prospective for each concept will be reviewed.

Logical probability: Let a finite set Ω containing n elements be given. If $A \subset \Omega$ contains k elements, the logical probability is the ratio of the number of elements in A to the number of elements in Ω.

$$p(A) = \frac{k}{n} \tag{B.1}$$

Objectivist's probability: Let an experiment be *repeatable* an infinite number of times, and let A be one possible outcome of the experiment. The objectivist's probability is the limit of the relative frequency of the occurrence of A given by

$$p(A) = \lim_{n \to \infty} \frac{S_n(A)}{n} \tag{B.2}$$

where $S_n(A)$ is the number of times A occurs in the first n repetitions of the experiment. In practice. one settles for as large an n as is logistically practical.

Subjectivist's probability: Let A be a statement that is or is not true. Then the subjectivist's probability is an individual's belief in A given by

$$p(A) = \text{'how strongly the individual feels } A \text{ is true (or will turn out to be true).'} \tag{B.3}$$

There are two major differences between the objectivist's probability and the subjectivist's probability. First, the objectivist's probability is a property of an entire sequence of trials. However, the subjectivist's probability is a property of a single trial. Second, the subjectivist's probability is personal. Two different people can have different subjective probabilities for the same event. However it is emphasized that they satisfy the following properties, regardless of their perspectives.

Kolmogorov Axioms for Probability Measure: Let A_i and A_j be any events defined on the sample space, Ω, of an experiment. With any event A_i, we associate a real number, $p(A_i)$, the *probability* *of* A_i, such that,

$$\begin{aligned} &p(\Omega) = 1 \\ &0 \leq p(A_i) \leq 1 \text{ if } A_i \subset \Omega \\ &p(A_i \cup A_j) = p(A_i) + p(A_j) \quad \text{if } A_i \cap A_j = \emptyset \end{aligned} \tag{B.4}$$

Some objectivists argue that the subjective probability does not need to satisfy the third axiom of the Kolmogorov axioms. This argument has been severely challenged by de Finetti with the *Dutch Book* theorem, that says that if a person is not coherent, then it is possible to set up a Dutch book against him or her. A Dutch book is a series of bets that guarantees your opponent will lose and you will win. For example, suppose that San Francisco 49ers and New England Patriots are in the Super Bowl. A person says that the probability is 0.5 that the 49ers will win and 0.4 that Patriots will win. If those really are his probabilities, then he should be willing to agree to the following lotteries:

```
Lottery 1: He wins $50 if 49ers win.
           You win $50 if 49ers lose.

Lottery 2: He wins $40 if Patriots lose.
           You win $60 if Patriots win.
```

Note that, according to his probabilities, his expected value for each lottery is zero. But the total expected value for the combined two lotteries is always -10 dollars, no matter what happens. This Dutch Book theorem says that a rational person should be coherent, i.e., his or her subjective probabilities should satisfy the Kolmogorov axioms, otherwise the rational person can lose his or her money always.

B.2.2 Conditional Probability

The joint probability of two events A_i and A_j is $p(A_i \cap A_j)$, written sometimes $p(A_i, A_j)$. A conditional probability of A_i given that A_j has occurred can be defined as:

$$p(A_i|A_j) = \frac{p(A_i, A_j)}{p(A_j)} \quad \text{if } p(A_j) \neq 0 \tag{B.5}$$

The *dependence* of two events is the case where knowledge as to whether or not one event occurs will have an effect on our estimate of the likelihood that the other will occur. Two events A_i and

A_j are *independent* if

$$p(A_i|A_j) = p(A_i) \tag{B.6}$$

In this situation, knowledge as to whether or not A_j has occurred has no effect on our estimate of the likelihood that A_i will occur. If two events are independent, the probability of their intersection may be obtained by multiplying the probabilities of the two events.

$$\begin{aligned} p(A_i, A_j) &= p(A_j)p(A_i|A_j) \\ &= p(A_i)p(A_j) \end{aligned} \tag{B.7}$$

B.2.3 Bayes' Rule

If $p(A_j) \neq 0$, then Bayes' rule says that

$$p(A_i|A_j) = \frac{p(A_j|A_i)p(A_i)}{p(A_j)} \tag{B.8}$$

If $A_i, i = 1, \ldots, n$ are mutually exclusive and $\cup A_i = \Omega$, then

$$p(A_i|B) = \frac{p(B|A_i)p(A_i)}{\sum_{i=1}^{n} p(B|A_i)p(A_i)} \tag{B.9}$$

B.3 Utility

B.3.1 Axioms of Rational Behavior

The *utility* of a consequence is a quantification of an individual's relative preference for that consequence based on the following axioms of rational behavior.

Comparison of simple lotteries with identical set of consequences If a decision maker prefers a consequence C^* to some other consequence C_*, he will prefer lottery $L_1 = L(C^*, C_*; p_1, 1-p_1)$ to lottery $L_2 = L(C^*, C_*; p_2, 1-p_2)$ if $p_1 > p_2$. If $p_1 = p_2$, he will be indifferent between L_1 and L_2, and if $p_1 < p_2$ he will prefer L_2 to L_1.

Quantification of preferences For a set of possible consequences $C_1, \ldots, C_m$, choose C^* and C_* such that $C_* \succeq C_i \succeq C_*$. For each C_i, the decision maker can specify a number $\Pi(C_i)$, such that he is indifferent between possessing C_i with certainty and possessing the lottery $L(C^*, C_*; \Pi(C_i), 1 - \Pi(C_i))$.

Quantification of uncertainty With C^* and C_* as defined earlier, let R refer to any event. For each R, the decision maker has a quantity $p(R)$, with $0 \leq p(R) \leq 1$, such that he is indifferent between the lottery $L(C^*, C_*; p(R), 1-p(R))$ and a lottery as a result of which he will possess C^* if R occurs and he will possess C_* if R does not occur.

Transitivity of preferences If C_1, C_2, and C_3 are consequences, then (i) $C_1 \sim C_2, C_2 \sim C_3$ implies $C_1 \sim C_3$ and (ii) $C_1 \succ C_2, C_2 \succ C_3$ implies $C_1 \succ C_3$.

Substitution of consequences If a decision problem is modified by replacing a consequence C_a with another consequence C_b, and if the decision maker is indifferent between the two consequences, he should be indifferent between possession of the original and possession of the modified decision problems.

Equivalence of preferences for actual and conjectural situation Let C_a and C_b be two consequences which are possible only if some chance event R occurs. After it is known that R occurred, the decision maker should have the same preference between C_a and C_b that he had before he knew whether or not R occurred.

B.3.2 Utility Functions

Consider a set of consequences $\{C_1, \ldots, C_m\}$. Let C^*, C_* be consequences, not necessarily in the set, satisfying $C^* \succeq C_i \succeq C_*$ for all i. The indifference probability or the preference value for C_i, $\Pi(C_i)$, is the probability that the individual is indifferent between possessing C_i for certain and possessing the lottery $L(C^*, C_*; \Pi(C_i), 1 - \Pi(C_i))$.

A utility function is a positive linear transformation of the indifference probability in the form of

$$U(C_i) = a\Pi(C_i) + b \quad \text{where } a > 0 \tag{B.10}$$

over the set of consequences. Note that a utility function can be translated vertically by changing a and b, however, it is not permissible to be translated horizontally.

With the preference value of each consequence, we can define the preference value of a lottery as the expectation of the preference values of the consequences of the lottery.

$$\Pi(L) = \sum_{i=1}^{m} p_i \Pi(C_i) \tag{B.11}$$

Consequently, the utility of a lottery is defined as

$$U(L) = \sum_{i=1}^{m} p_i U(C_i) \tag{B.12}$$

B.3.3 Optimal Decision

A decision analysis is how rational people should make a decision based on the probabilities and the utility of the possible consequences of the decision.

Suppose a decision maker faces a decision-making problem with two possible decisions D_a, D_b. Let $C_{a1}, \ldots, C_{am}$ be possible consequences of the decision D_a and $C_{b1}, \ldots, C_{bm}$ be possible consequences of the decision D_b. Then a rational decision maker should choose a decision which maximizes the utility of a decision

$$U(D_i) = \sum_{j=1}^{m} p(C_{ij}) U(C_{ij}) \tag{B.13}$$

The optimal decision is

$$d^* = \arg\max_i U(D_i) \tag{B.14}$$

Appendix C

On Optimization

The purpose of this appendix is to provide a brief review of the optimization theory which is used in developing the theory of human intervention. For details, see references such as [4].

C.1 Principle of Optimality

Let $d^* = \{d_1^*, d_2^*, \ldots, d_{N-1}^*\}$ be an optimal policy for the time period $\{1, \ldots, N\}$ from a state x_o to a state x_f, and assume that a state x_i occurs at time i when using d^*. Consider the subproblem from the state x_i to the state x_f, then the truncated policy $\{d_i^*, \ldots, d_{N-1}^*\}$ is optimal for the subproblem.

For an auto travel analogy, suppose that the fastest route from Boston to New York passes through Hartford. Then the portion of route from Hartford to New York is, in fact, the fastest route from Hartford to New York.

C.2 Dynamic Programming

We are given a discrete-time dynamic system

$$x_{k+1} = f_k(x_k, u_k, w_k) \tag{C.1}$$

where $k = 0, \ldots, N-1$, and the state x_k is an element of a space X, the control u_k is an element of a space U, and the disturbance w_k is an element of a space of W. A cost function is given for an initial state x_0 as

$$J(x_0) = \mathrm{E}\left[g_N(x_N) + \sum_{i=0}^{N-1} g_i(x_i, u_i, w_i)\right] \tag{C.2}$$

Let $J_k^*(x_k)$ be the optimal cost with an initial state x_k from time k to the final time N, i.e.,

$$J_k^*(x_k) = \min \mathrm{E}\left[g_N(x_N) + \sum_{i=k}^{N-1} g_i(x_i, u_i, w_i)\right] \tag{C.3}$$

Then for each time k, the optimal cost $J_k^*(x_k)$ is

$$J_k^*(x_k) = \min \mathrm{E}\left[g_k(x_k, u_k, w_k) + J_{k+1}^*(f_k(x_k, u_k, w_k))\right] \tag{C.4}$$

and

$$J_N^*(x_N) = g_N(x_N) \tag{C.5}$$

where the expectation is taken with respect to the probability distribution of w_k, which depends on x_k and u_k. The procedure to solve for the optimal cost is to proceed backward in time from time $N-1$ to time 1.

Appendix D

Subject Consent Form

The U. S. Department of Health and Human Services requires that all persons used as subjects in experiments sign a consent agreement.

The procedures to be followed in our experiments involve making observations from a computer or related displays, making decisions and communicating these by mechanical or verbal means to be provided and explained to you in detail. These experiments do not, in our judgment, pose any risks or hazards to your health or well-being. You are free to ask any questions and have them answered to your satisfaction, and are free to withdraw consent and discontinue participating at any time without prejudice.

I understand that I may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, Dr. H. Walter Jones, E23-425, MIT (tel. 253-1772), if I feel I have been treated unfairly as a subject, and that further information may be obtained by calling the MIT Insurance and Legal Affairs Office, 4-104 (tel. 253-2822).

I consent to be a subject in the MIT Human-Machine Systems Laboratory under the above stated conditions.

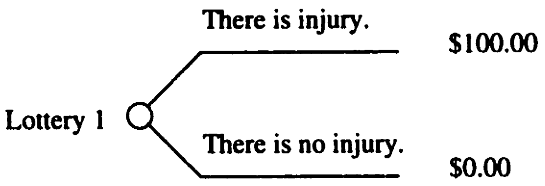
(name)	(signature)	(date)

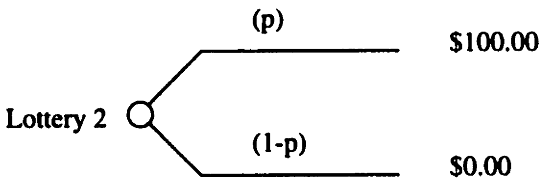
Appendix E

Questionnaires for Experiment 1 and 2

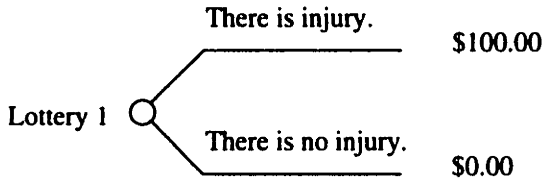
This questionnaire was given to the experimental subjects after experiment 1 and 2 had been completed. The answers provided on this questionnaire were used to assess the subjective probability of characteristics of an incident.

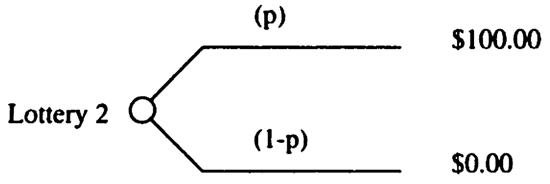
1. Suppose the decision aid says that there is injury and your observation says that there is no injury. Then which lottery do you prefer between the following two lotteries with the given probability *p*?





2. Suppose the decision aid says that there is no injury and your observation says that there is injury. Then which lottery do you prefer between the following two lotteries with the given probability *p*?





3. Suppose the probability of injury for a given incident is p. Then would you dispatch an EMS with the given probability p?

Appendix F

Trials and Corresponding Response Plans

The following tables show the trials used in experiment 1, 2, 3, and 4 and corresponding correct response plan. The order of information given in experiment 1 and 2 is injury, fire, *and* spill. *For the plan,* E, P, F, *and* M *indicate* ERT, MSP, BFD, *and* EMS, *respectively.*

Table F.1: Experiment 1 and 3

TRIAL	INJURY	FIRE	SPILL	PLAN
11	no	no	no	EP
12	no	no	minor	EP
13	no	no	major	EPF
14	no	minor	no	EP
15	no	minor	minor	EP
16	no	minor	major	EPF
17	no	major	no	EPF
18	no	major	minor	EPF
19	no	major	major	EPF
1a	yes	no	no	EPM
1b	yes	no	minor	EPM
1c	yes	no	major	EPFM
1d	yes	minor	no	EPM
1e	yes	minor	minor	EPM
1f	yes	minor	major	EPFM
1g	yes	major	no	EPFM
1h	yes	major	minor	EPFM
1i	yes	major	major	EPFM

Table F.2: Experiment 2 and 4

TRIAL	INJURY	FIRE	SPILL	PLAN
21	no	no	no	EP
22	no	no	minor	EP
23	no	no	major	EPF
24	no	minor	no	EP
25	no	minor	minor	EP
26	no	minor	major	EPF
27	no	major	no	EPF
28	no	major	minor	EPF
29	no	major	major	EPF
2a	yes	no	no	EPM
2b	yes	no	minor	EPM
2c	yes	no	major	EPFM
2d	yes	minor	no	EPM
2e	yes	minor	minor	EPM
2f	yes	minor	major	EPFM
2g	yes	major	no	EPFM
2h	yes	major	minor	EPFM
2i	yes	major	major	EPFM

Appendix G

Individual Experimental Data

The following tables show that what information was sought and how a suggested response plan was modified by each subject in experiment 1, 2, 3, and 4. The order of information given in experiment 1 and 2 is injury, fire, *and* spill. *For the searching suggested in experiment 3 and 4,* F *stands for fire and* S *stands for spill. For the plan suggested and the plan executed in experiment 1, 2, 3, and 4,* E, P, F, *and* M *indicate ERT, MSP, BFD, and EMS, respectively. Since the performance of the decision aid in the experiments is not 100%, the suggested plans were different from subject to subject for the same trials. Time is the time taken for making a response plan excluding time taken for searching additional information in a unit of minute.*

Table G.1: Subject A in Experiment 1

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	yes, no, no	fire, spill	no, no	EPM	EPM	0.5592
12	no, minor, minor	injury, fire	yes, no	EP	EPM	0.5008
13	no, no, major	injury, fire	no, minor	EPF	EPF	0.4564
14	no minor, major	injury	no	EPF	EPF	0.3647
15	no, minor, minor	injury, fire	yes, minor	EP	EPM	0.5472
16	no, minor, no	injury, fire	yes, minor	EP	EPFM	0.9553
17	no, major, no	injury	yes	EPF	EPFM	1.0642
18	no, minor, minor	injury, spill	yes, minor	EP	EPM	0.5306
19	no, no, no	injury, fire	no, major	EP	EPFM	0.5408
1a	yes, no, no	fire, spill	no, no	EPM	EPM	0.3108
1b	yes, minor, minor	fire, spill	minor, minor	EPM	EPM	0.4964
1c	yes, major, major	no		EPFM	EPFM	0.2042
1d	yes, minor, no	fire, spill	minor, no	EPM	EPM	0.5589
1e	yes. minor, minor	fire, spill	minor, minor	EPM	EPM	0.4983
1f	no, minor, no	injury, spill	no, major	EP	EPF	0.5081
1g	yes, major, no	spill	no	EPFM	EPFM	0.3100
1h	no, major, minor	injury	no	EPF	EPF	0.3647
1i	yes, major, minor	no		EPFM	EPFM	0.3447

Table G.2: Subject B in Experiment 1

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	no, no, no	no		EP	EP	0.3428
12	no, no, minor	no		EP	EPM	0.4025
13	no, no, major	no		EPF	EPF	0.1947
14	no, minor, no	no		EP	EP	0.1383
15	no, minor, minor	no		EP	EP	0.1144
16	no, minor, major	no		EPF	EPF	0.1608
17	yes, major, no	no		EPFM	EPFM	0.2270
18	yes, major, minor	no		EPFM	EPFM	0.1203
19	no, major, major	no		EPF	EPF	0.1686
1a	yes, no, no	no		EPM	EPM	0.2308
1b	no, no, major	no		EPF	EPF	0.1480
1c	yes, no, major	no		EPFM	EPFM	0.1297
1d	yes, no, no	no		EPM	EPM	0.2089
1e	no, minor, major	no		EPF	EPF	0.4108
1f	yes, minor, minor	no		EPM	EPFM	0.4195
1g	yes, major, no	no		EPFM	EPFM	0.3303
1h	yes, no, no	no		EPM	EPM	0.1483
1i	no, major, minor	no		EPF	EPF	0.1675

Table G.3: Subject C in Experiment 1

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN TIME EXECUTED	(MIN)
11	yes, no, no	injury	no	EPM	EPM	0.2295
12	yes, no, minor	spill	no	EPM	EPM	0.2731
13	yes, no, major	injury, spill	no, major	EPFM	EPFM	0.4536
14	no, minor, no	no		EP	EP	0.2167
15	no, minor, major	injury	no	EPF	EPF	0.6945
16	no, minor, major	injury	yes	EPF	EPFM	0.4203
17	yes, major, major	injury	no	EPFM	EPFM	0.5372
18	no, major, minor	no		EPF	EPF	0.2558
19	no, no, major	injury, spill	no, no	EPF	EP	0.3933
1a	yes, no, no	injury	no	EPM	EPM	0.8767
1b	yes, no, minor	injury, spill	no, no	EPM	EPM	0.3383
1c	yes, no, major	injury	no	EPFM	EPFM	0.6614
1d	yes, minor, no	fire	minor	EPM	EPM	0.4280
1e	no, minor, minor	no		EPM	EPM	0.3067
1f	yes, minor, major	injury	yes	EPFM	EPFM	0.3808
1g	yes, no, no	injury	no	EPM	EPM	0.3098
1h	yes, major, minor	injury	yes	EPFM	EPFM	0.3114
1i	yes, major, major	injury	no	EPFM	EPFM	0.2853

Table G.4: Subject D in Experiment 1

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	no, no, no	no		EP	EP	0.2211
12	yes, major, minor	no		EPFM	EPFM	0.3200
13	no, no, major	no		EPF	EPF	0.4883
14	yes, minor, no	no		EPM	EPM	0.1967
15	no, minor, minor	no		EP	EP	0.2028
16	no, minor, major	no		EPF	EPF	0.4317
17	no, major, major	no		EPF	EPFM	0.3528
18	yes, major, minor	no		EPFM	EPFM	0.3439
19	no, major, major	no		EPF	EPF	0.2606
1a	no, no, no	no		EP	EP	0.2742
1b	yes, no, minor	no		EPM	EPM	0.5842
1c	yes, no, major	no		EPFM	EPFM	0.2433
1d	yes, no, minor	no		EPM	EPM	0.3253
1e	no, minor, minor	no		EP	EP	0.3561
1f	yes, no, major	no		EPFM	EPFM	0.2022
1g	yes, major, no	no		EPFM	EPFM	0.4375
1h	yes, major, no	no		EPFM	EPFM	0.2094
1i	no, major, major	no		EPF	EPF	0.2272

Table G.5: Subject E in Experiment 1

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	no, major, no	no		EPF	EP	0.3167
12	yes, no, minor	no		EPM	EPM	0.4514
13	no, no, major	no		EPF	EP	0.4097
14	no, minor, no	no		EP	EPM	0.3353
15	no, minor, minor	no		EP	EP	0.3597
16	yes, minor, no	no		EPM	EPM	0.6119
17	no, no, no	no		EP	EPF	0.3486
18	no, major, minor	no		EPF	EPF	0.3942
19	no, major, major	no		EPF	EPF	0.3792
1a	yes, no, minor	no		EPM	EPM	0.3903
1b	no, no, major	no		EPF	EP	0.4414
1c	yes, no, major	no		EPFM	EPFM	0.4342
1d	yes, minor, no	no		EPM	EPM	0.4203
1e	no, no, minor	no		EP	EP	0.2817
1f	yes, minor, major	no		EPFM	EPFM	0.3148
1g	yes, major, no	no		EPFM	EPFM	0.1578
1h	yes, major, minor	no		EPFM	EPFM	0.4239
1i	yes, minor, no	no		EPM	EPM	0.6086

Table G.6: Subject A in Experiment 2

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	yes, no, no	fire	no	EPM	EPM	0.7289
22	no, no, minor	injury	no	EP	EP	1.0020
23	no, no, minor	injury, spill	no, no	E	E	1.3953
24	no minor, no	fire	minor	EP	EP	0.7320
25	yes, minor, minor	fire	no	EPM	EPM	0.8472
26	no, minor, major	injury	no	EPF	EPF	0.4703
27	no, major, no	fire, injury	major, no	EPF	EPF	0.7550
28	no, major, minor	injury	no	EPF	EPF	0.5555
29	no, no, major	injury	no	EPF	EPF	0.6736
2a	yes, no, minor	spill	no	EPM	EPM	0.9086
2b	yes, no, minor	spill	minor	EPM	EPM	0.5664
2c	yes, major, major	injury	yes	EPFM	EPFM	0.5006
2d	yes, minor, no	fire	minor	EPM	EPM	0.7794
2e	no, minor, major	injury	yes	EPF	EPFM	0.7283
2f	no, minor, major	no		EPF	EPF	0.3442
2g	yes, major, no	fire, injury	major, yes	EPFM	EPFM	1.4214
2h	yes, major, minor	no		EPFM	EPFM	0.4417
2i	yes, major, minor	injury	yes	EPFM	EPFM	0.5722

Table G.7: Subject B in Experiment 2

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	yes, no, no	no		EPM	EPM	0.2631
22	no, minor, minor	no		EP	EP	0.5025
23	no, no, major	no		EPF	EPF	0.2383
24	no, minor, no	injury	no	EP	EP	0.4811
25	no, minor, minor	fire	minor	EP	EP	0.3414
26	no, major, major	no		EPF	EPF	0.2161
27	no, major, no	fire	major	EPF	EPF	0.4433
28	yes, major, major	no		EPFM	EPFM	0.1297
29	no, no, major	no		EPF	EPF	0.2067
2a	no, minor, no	no		EP	EP	0.2883
2b	yes, minor, major	no		EPFM	EPFM	0.1380
2c	yes, minor, major	no		EPFM	EPFM	0.4900
2d	yes, minor, no	no		EPM	EPM	1.0628
2e	no, minor, minor	fire	minor	EP	EP	0.3606
2f	no, minor, major	no		EPF	EPF	0.3044
2g	yes, major, no	no		EPFM	EPFM	0.4155
2h	yes, major, minor	no		EPFM	EPFM	0.1986
2i	yes, major, major	no		EPFM	EPFM	0.1730

Table G.8: Subject C in Experiment 2

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	yes, minor, no	fire	no	EPM	EPM	0.3500
22	no, no, minor	injury	no	EP	EP	0.2547
23	no, no, minor	injury	yes	EP	EPM	0.4211
24	yes, minor, minor	injury	no	EPM	EP	0.5839
25	no, minor, major	injury	no	EPF	EPF	0.3492
26	yes, minor, major	injury, spill	no, major	EPFM	EPF	0.5242
27	no, major, no	injury	no	EPF	EPF	0.3686
28	no, minor, minor	injury	no	EP	EPF	0.2853
29	yes, no, major	injury, spill	no, major	EPFM	EPF	0.5895
2a	no, no, major	injury, spill	yes, no	EPF	EPM	0.4875
2b	yes, major, minor	fire, injury	no, yes	EPFM	EPM	0.5822
2c	yes, no, minor	spill	major	EPM	EPFM	0.3536
2d	yes, minor, major	injury	yes	EPFM	EPFM	0.4261
2e	yes, minor, minor	fire	minor	EPM	EPM	0.6728
2f	yes, minor, major	injury	no	EPFM	EPF	0.5700
2g	no, major, minor	injury	no	EPF	EPF	0.2983
2h	yes, major, minor	injury	yes	EPFM	EPFM	0.5114
2i	yes, major, major	no		EPFM	EPFM	0.1681

Table G.9: Subject D in Experiment 2

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	no, major, no	no		EPF	EP	0.3655
22	no, minor, minor	no		EP	EP	0.1722
23	yes, no, major	no		EPFM	EP	0.2067
24	no, minor, major	no		EPF	EPF	0.3417
25	no, minor, minor	no		EP	EPM	0.2208
26	no, no, major	no		EPF	E	0.3197
27	no, major, no	no		EPF	EP	0.2419
28	no, major, minor	no		EPF	EP	0.2886
29	yes, major, no	no		EPFM	EP	0.3583
2a	yes, no, no	no		EPM	EP	0.3567
2b	no, no, major	no		EPF	EP	0.2225
2c	yes, no, no	no		EPM	EP	0.2514
2d	no, minor, no	no		EP	E	0.2078
2e	yes, minor, no	no		EPM	E	0.3395
2f	yes, minor, major	no		EPFM	EP	0.2919
2g	yes, major, no	no		EPFM	EPF	0.2831
2h	yes, major, no	no		EPFM	E	0.3883
2i	yes, major, no	no		EPFM	EP	0.2761

Table G.10: Subject E in Experiment 2

TRIAL	INFORMATION GIVEN	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	no, no, no	no		EP	EP	0.3236
22	no, no, minor	no		EP	E	0.5147
23	no, no, major	no		EPF	EP	0.5411
24	no, minor, no	no		EP	EP	0.5808
25	no, minor, minor	no		EP	EP	0.4555
26	no, minor, minor	no		EP	EP	0.3000
27	no, minor, no	no		EP	EP	0.3458
28	no, minor, minor	no		EP	EPM	0.3178
29	no, no, no	no		EP	E	0.2822
2a	no, no, no	no		EP	EP	0.4511
2b	yes, no, minor	no		EPM	EPM	0.2858
2c	yes, no, major	no		EPFM	EPFM	0.3275
2d	yes, minor, no	no		EPM	EP	0.3914
2e	no, minor, minor	no		EP	EP	0.3369
2f	yes, minor, major	no		EPFM	EPFM	0.3286
2g	yes, major, no	no		EPFM	EPFM	0.3150
2h	yes, major, major	no		EPFM	EPFM	0.3342
2i	yes, no, major	no		EPFM	EPM	0.5522

Table G.11: Subject F in Experiment 3

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	no	no		EPFM	EPFM	0.1456
12	no	no		EP	EP	0.1553
13	no	no		EPFM	EPFM	0.0780
14	no	no		EPF	EPF	0.0742
15	no	no		EPM	EPM	0.0694
16	no	no		EPF	EPF	0.0614
17	no	no		EP	EP	0.0647
18	no	no		EPM	EPM	0.0547
19	no	no		EPF	EPF	0.0536
1a	no	no		EP	EP	0.0642
1b	no	no		EPFM	EPFM	0.0786
1c	no	no		EPFM	EPFM	0.0650
1d	no	no		EPM	EPM	0.0567
1e	no	no		EPM	EPM	0.0556
1f	no	no		EPF	EPF	0.1633
1g	no	no		EPM	EPM	0.1958
1h	no	no		EPFM	EPFM	0.1161
1i	no	no		EPFM	EPFM	0.0955

Table G.12: Subject G in Experiment 3

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	no	no		EP	EP	0.1167
12	no	no		EPM	EPM	0.0683
13	no	no		EP	EP	0.1786
14	no	no		EP	EP	0.1155
15	no	no		EPF	EPF	0.0722
16	no	no		EPFM	EPFM	0.0756
17	no	no		EPM	EPM	0.1395
18	no	no		EPF	EPF	0.0595
19	no	no		EPF	EPF	0.0517
1a	no	no		EPFM	EPFM	0.1125
1b	no	no		EPFM	EPFM	0.1153
1c	no	no		EPFM	EPFM	0.0572
1d	no	no		EPFM	EPFM	0.0833
1e	no	no		EPM	EPM	0.0783
1f	no	no		EPFM	EPFM	0.0670
1g	no	no		EPF	EPF	0.1528
1h	no	no		EPFM	EPFM	0.0675
1i	no	no		EPFM	EPFM	0.1208

Table G.13: Subject H in Experiment 3

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	no	no		EP	EP	0.1250
12	no	no		EPM	EPM	0.0753
13	no	no		EP	EP	0.0792
14	no	no		EP	EP	0.0856
15	no	no		EP	EP	0.1147
16	no	no		EPF	EPF	0.0747
17	no	no		EPF	EPF	0.0744
18	no	no		EPF	EPF	0.1025
19	no	no		EPF	EPF	0.1225
1a	no	no		EPM	EPM	0.0764
1b	no	no		EPM	EPM	0.0750
1c	no	no		EP	EP	0.1164
1d	no	no		EPM	EPM	0.0780
1e	no	no		EPM	EPM	0.0611
1f	no	no		EPFM	EPFM	0.1333
1g	no	no		EPF	EPF	0.1095
1h	no	no		EPFM	EPFM	0.1222
1i	no	no		EPF	EPF	0.0689

Table G.14: Subject I in Experiment 3

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	no	no		EP	EP	0.0672
12	no	no		EPF	EPF	0.0628
13	no	no		EPFM	EPFM	0.0622
14	no	no		EP	EP	0.0544
15	no	no		EPF	EPF	0.0897
16	no	no		EPFM	EPFM	0.1200
17	no	no		EPM	EPM	0.0820
18	no	no		EPF	EPF	0.0739
19	no	no		EPFM	EPFM	0.0533
1a	no	no		EPM	EPM	0.0586
1b	no	no		EPF	EPF	0.0630
1c	no	no		EPM	EPM	0.1131
1d	no	no		EP	EP	0.1061
1e	no	no		EPM	EPM	0.1492
1f	no	no		EPFM	EPFM	0.0911
1g	no	no		EPFM	EPFM	0.0750
1h	no	no		EPM	EPM	0.0581
1i	no	no		EPFM	EPFM	0.0980

Table G.15: Subject J in Experiment 3

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
11	no	no		EPF	EPF	0.0675
12	no	no		EPF	EPF	0.0639
13	no	no		EPM	EPM	0.1175
14	no	no		EPFM	EPFM	0.0722
15	no	no		EP	EP	0.1555
16	no	no		EPF	EPF	0.0747
17	no	no		EPF	EPF	0.0742
18	no	no		EPF	EPF	0.1308
19	no	no		EPFM	EPFM	0.0678
1a	no	no		EPM	EPM	0.0650
1b	no	no		EP	EP	0.0680
1c	no	no		EPFM	EPFM	0.0575
1d	no	no		EPM	EPM	0.0686
1e	no	no		EPM	EPM	0.0728
1f	no	no		EPM	EPM	0.0933
1g	no	no		EPFM	EPFM	0.0897
1h	no	no		EPFM	EPFM	0.0572
1i	no	no		EPFM	EPFM	0.1155

Table G.16: Subject F in Experiment 4

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	no	no		EP	EP	0.1300
22	no	no		EPM	EPM	0.0911
23	S	S	major	EP	EPF	0.3742
24	no	no		EP	EP	0.1339
25	no	no		EP	EP	0.0800
26	S	S	major	EP	EPF	0.2455
27	F	F	major	EP	EPF	0.2033
28	F	F	major	EP	EPF	0.1492
29	F	F	major	EP	EPF	0.1808
2a	no	no		EPM	EPM	0.1025
2b	no	no		EPM	EPM	0.0786
2c	no	no		EPM	EPM	0.1464
2d	no	no		EPM	EPM	0.0853
2e	S	S	minor	EPM	EPM	0.1833
2f	F	F	minor	EPM	EPM	0.2617
2g	no	no		EPM	EPM	0.0842
2h	F	F	major	EPM	EPFM	0.1930
2i	F,S	no		EPM	EPFM	0.0992

Table G.17: Subject G in Experiment 4

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	S	S	no	EP	EP	0.2006
22	no	no		EPM	EPM	0.0805
23	S	S	major	EP	EPF	0.2067
24	F	F	minor	EP	EP	0.2208
25	S	S	minor	EPM	EPM	0.2508
26	S	S	major	EP	EPF	0.1786
27	F	F	major	EP	EPF	0.2781
28	no	no		EP	EP	0.1103
29	S	S	major	EP	EPF	0.2028
2a	S	S	no	EP	EP	0.1881
2b	no	no		EPM	EPM	0.1033
2c	S	S	major	EPM	EPFM	0.2028
2d	no	no search		EPM	EPM	0.0797
2e	no	no search		EP	EP	0.0867
2f	S	S	major	EP	EPFM	0.3164
2g	F	F	major	EPM	EPFM	0.2089
2h	F,S	no		EPM	EPFM	0.1208
2i	F,S	no		EPM	EPFM	0.1183

Table G.18: Subject H in Experiment 4

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	F,S	no		EPM	EPFM	0.1480
22	no	no		EP	EP	0.0789
23	no	no		EP	EP	0.0761
24	no	no		EPM	EPM	0.0808
25	no	no		EP	EP	0.1372
26	F,S	no		EP	EPF	0.1131
27	F	F	no	EP	EP	0.2897
28	F	F	major	EP	EPF	0.1586
29	S	S	major	EP	EPF	0.1472
2a	no	no		EPM	EPM	0.0839
2b	no	no		EPM	EPM	0.0805
2c	S	S	major	EPM	EPFM	0.1478
2d	F	F	minor	EPM	EPM	0.1814
2e	no	no		EPM	EPM	0.1553
2f	no	no		EPM	EPM	0.0925
2g	F	F	major	EPM	EPFM	0.1945
2h	F	F	major	EPM	EPFM	0.1542
2i	F,S	no		EP	EPF	0.0950

Table G.19: Subject I in Experiment 4

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	no	no		EP	EP	0.0789
22	F	F	no	EP	EP	0.1797
23	S	S	major	EP	EPF	0.2233
24	S	S	no	EP	EP	0.2189
25	no	no		EP	EP	0.1545
26	no	no		EPM	EPM	0.0856
27	F	F	major	EP	EPF	0.2197
28	F	F	major	EPM	EPFM	0.1908
29	F,S	no		EP	EPF	0.1114
2a	no	no		EPM	EPM	0.0750
2b	no	no		EP	EP	0.0775
2c	S	S	major	EPM	EPFM	0.2342
2d	S	S	no	EP	EP	0.2414
2e	no	no		EP	EP	0.0739
2f	no	no		EP	EP	0.1347
2g	F	F	major	EPM	EPFM	0.1720
2h	F,S	no		EPM	EPFM	0.0950
2i	F,S	no		EPM	EPFM	0.1089

Table G.20: Subject J in Experiment 4

TRIAL	SEARCHING SUGGESTED	INFORMATION SOUGHT	SEARCHING RESULT	PLAN SUGGESTED	PLAN EXECUTED	TIME (MIN)
21	no	no		EPM	EPM	0.0897
22	F	F	no	EP	EP	0.2089
23	no	no		EP	EP	0.1667
24	no	no		EP	EP	0.1072
25	no	no		EP	EP	0.0936
26	S	S	major	EP	EPF	0.1783
27	F	F	major	EP	EPF	0.2089
28	F	F	major	EP	EPF	0.2403
29	F	F	major	EP	EPF	0.2045
2a	no	no		EPM	EPM	0.1442
2b	F	F	no	EPM	EPM	0.2161
2c	no	no		EPM	EPM	0.1175
2d	no	no		EPM	EPM	0.1617
2e	no	no		EP	EP	0.1686
2f	S	S	major	EPM	EPFM	0.2567
2g	F	F	major	EPM	EPFM	0.1989
2h	F,S	no		EP	EPF	0.1983
2i	F,S	no		EPM	EPFM	0.1417

S.D.G.