A Dynamic Programming Algorithm for Scheduling In-Vehicle Messages

Hansuk Sohn, John D. Lee, Dennis L. Bricker, and Joshua D. Hoffman

***Abstract*—In-vehicle information systems (IVISs) can enhance or compromise driving safety. Such systems present an array of messages that range from collision warnings and navigation instructions to tire pressure and e-mail alerts. If these messages are not properly managed, the IVIS might fail to provide the driver with critical information, which could undermine safety. In addition, if the IVIS simultaneously presents multiple messages, the driver may fail to attend to the most critical information. To date, only simple algorithms that use priority-based filters have been developed to address this problem. This paper presents a dynamic programming model that goes beyond the immediate relevance and urgency parameters of the current Society of Automotive Engineers (SAE) message scheduling algorithm. The resulting algorithm considers the variation of message value over time, which extends the planning horizon and creates a more valuable stream of messages than that based only on the instantaneous message priority. This method has the potential to improve road safety because the most relevant information is displayed to drivers across time and not just the highest priority at any given instant. Applying this algorithm to message sets shows that scheduling that considers the time-based message value, in addition to priority, results in substantially different and potentially better message sequences compared with those based only on message priority. This method can be extended to manage driver workload by adjusting message timing relative to demanding driving maneuvers.**

***Index Terms*—Distraction, dynamic programming (DP), in-vehicle information systems (IVISs), task scheduling.**

I. Introduction

RECENT technological advances have made a wide variety of information systems for cars and trucks possible. New sensor capabilities, global positioning systems, the Internet, and wireless communication constitute four particularly important technologies that are capable of dramatically altering driving. These technologies make it possible for in-vehicle information systems (IVISs) to provide drivers with an array of information, such as cell phone calls, MP3 music catalogs, e-mail, route guidance, vehicle status, and collision warnings [1]–[3]. The number and diversity of these systems presents drivers with the challenge of detecting and responding to a large number of messages and alerts. This wealth of information requires that drivers decide when to attend to various IVIS messages and roadway events [4]. If IVIS functions are implemented without concern for how they may interact, the combination may burden drivers with the challenge of attending to a confusing array of messages. Failing to properly distribute attention to these competing demands could jeopardize safety.

In complex dynamic tasks, such as operating a vehicle, operators must frequently perform several subtasks that serve different task goals. Cnossen *et al.* [5] specifically examined whether drivers give less priority to tasks external to driving than they do to tasks that more directly serve driving. The results showed that drivers tended to shed nondriving secondary tasks as roadway demands increase but continued to attend to a driving-related secondary task, interacting with a navigation system, even when their driving performance degraded. Drivers do not always effectively manage tasks; such task management, however, is a critical contributor to performance in complex dynamic multitask situations [6].

People are limited in their ability to manage their attention when faced with complex sequences of tasks. Tulga and Sheridan [7] studied the workload of operators in multitask supervisory control settings and found that increasing the number of tasks degrades performance because when tasks overload the capacity to respond, people tend to respond to immediate task demands and neglect the future demands. A study comparing the workload management of experienced and novice pilots showed that experienced pilots shed less important tasks to attend to critical tasks more effectively than novice pilots but that both groups did not always effectively manage their workload [8].

Multiple information systems might have a similar effect, generating an array of competing messages that drivers, particularly younger drivers, may not be able to attend to appropriately [9]. One study investigated the effect of multiple IVISs on drivers' ability to control the vehicle. The study showed that interactions with multiple in-vehicle systems were significantly more detrimental to driving than interactions with single in-vehicle systems [10]. Another study considered how interaction modality might moderate the potential information overload associated with multiple IVISs. When confronted with visual, auditory, and combined visual and auditory secondary tasks, driving performance declined to a similar degree [11]. These results suggest that simply shifting the modality by which the information is presented will not avoid overload and that messages need to be managed [12].

Prioritizing messages might help avoid overloading the driver with IVIS messages. Early efforts to establish message

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H. Sohn is with the Department of Industrial Engineering, College of Engineering, New Mexico State University, Las Cruces, NM 88003 USA (e-mail: hsohn@nmsu.edu).

J. D. Lee, D. L. Bricker, and J. D. Hoffman are with the Department of Mechanical and Industrial Engineering, College of Engineering, University of Iowa, Iowa City, IA 52242 USA (e-mail: jdlee@engineering.uiowa.edu; dbricker@engineering.uiowa.edu; jhoffman@engineering.uiowa.edu).

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TABLE I
PRIORITIZATION CRITERIA IN SAE J2395

Criteria	Levels	Examples
Safety Relevance	Directly	A message relaying an imminent collision notification.
	Indirectly/Somewhat	A suggested navigation route that reduces travel time/distance.
	Not	An incoming call indicator on a cellular phone.
Operational Relevance	Highly	Notification of an engine temperature warning.
	Moderately	The distance to the destination on a navigation system.
	Little or No	The stereo indicator on an entertainment system.
Time Urgency	Emergency: 0-3 s	Brake immediately
	Immediate: 3-10 s	Road work area within 5 seconds.
	Near Term: 10-20 s	Obstacle within 15 seconds in the vehicle's path.
	Preparatory:20-120 s	Prepare to take action to the information within 60 seconds.
	Discretionary: > 120 s	No direct action or decision required by driver.

priority included subjective rank ordering of message urgency by drivers [13] and priority assignment based on expert judgment [14]. A more adaptive system that incorporates the current driving situation into the priority value has also been proposed [14], [15]. These methods, which are viable means of defining message priority, suggest a "highest priority first" algorithm to be used to determine what message to display. The remaining messages are then queued according to descending priority. This approach, however, can lead to the display of obsolete messages or to the inability to display a message because it is repeatedly superseded by newer higher priority messages. Also, a priority scheduling method does not account for equally prioritized messages, whereby messages will compete to be displayed whenever they are scheduled in close temporal proximity. Most importantly, a currently available low-priority message could inappropriately delay the display of a high-priority message if the high-priority message was triggered slightly later than the low-priority message. Presenting messages only according to priority and failing to consider the value of future messages could undermine the safety benefit of IVISs.

Recently, the Society of Automotive Engineers (SAE) and the International Organization for Standardization (ISO) established in-vehicle message priority standards [16], [17]. These two standards both use safety relevance and time urgency to determine message priority. However, the number of criteria, the number of levels, the basic method, and the priority index differ. In this paper, we focus on the SAE method, since it has proved to be more successful compared to the ISO method.

As shown in Table I, SAE uses three criteria (safety relevance, operational relevance, and time urgency) to define the priority order index (POI). A panel of transportation experts defined the POI associated with each combination of levels. Table II shows examples of in-vehicle messages and their POI value for all combinations of these criteria. SAE J2395 contains more detail [16].

While the SAE standard improves on previous approaches by establishing a systematic method to define priority, it still resorts to a "highest-priority first" (lowest POI) algorithm, neglecting the time course of message value and message conflict. As with the early prioritization methods, the POI approach neglects the dynamic nature of driving—the POI for each message is computed, irrespective of the time course of messages. For example, when the display becomes available, the message having the smallest POI (i.e., highest priority) at that instant is chosen without considering the effect of postponing competing messages. It also does not consider the effect of displaying a message on the display of future messages. Message scheduling should consider temporal considerations that go beyond message priority because the delays that could otherwise develop could undermine safety [18]. Including temporal dynamics in the ordering and timing of messages requires an approach that includes the value of messages over time. Researchers have begun to confront this challenge. One approach used a branch-and-bound algorithm that searches for a set of tasks that will meet their deadlines. This approach considers the cost of missing deadlines and delaying high-priority tasks [19]. We solve the more general problem of identifying the best time to present a message based on the time-dependent value of message presentation using a recursive dynamic programming (DP) technique.

DP is an optimization procedure that is particularly applicable to problems requiring a series of time-dependent interrelated decisions, such as sequencing and scheduling. DP was first developed by Bellman in 1957. Held and Karp [20] then applied DP ideas to sequencing problems. There have been many applications of DP to sequencing and scheduling [21], [22]. However, there has been no attempt to implement the DP technique to schedule the presentation of IVIS messages.

This paper is organized as follows: In Section II, we present a DP model of the message presentation problem. An example is used to illustrate the computational method in Section III. In Section IV, another example is described to compare the performance of the DP algorithm to that of the SAE approach. Section V presents conclusions, followed by a discussion of the unresolved issues that merit further research in Section VI.

II. DP MODEL

We treat the message-presentation problem as a sequential decision problem, in which we are given a set of messages and their characteristics (indications of their importance, duration, and preferred display time) and must decide which messages to display at what time. In this situation, a new decision may be required before a previous decision has been carried out;

TABLE II
EXAMPLE APPLICATION OF POI FROM SAE J2395

Safety	Operation	Time	Example Message	Priority Order Index
Directly	Highly	Emergency 0-3 s	Collision imminent	1
Directly	Highly	Immediate 3-10 s	Object in roadway	2
Directly	Moderate	Emergency 0-3 s	Lane ends 500 feet	3
Directly	Moderate	Immediate 3-10 s	Hood ajar	4
Directly	Little/No	Emergency 0-3 s	Driver fatigue detected	5
Directly	Highly	Near Term 10-20 s	Tire pressure falling	6
Directly	Moderate	Near Term 10-20 s	Lane ends in 1 mile	7
Somewhat	Highly	Emergency 0-3 s	Vehicle in blind spot, avoid lane change	8
Directly	Little/No	Immediate 3-10 s	Passenger door ajar	9
Directly	Highly	Preparatory 20-120 s	Accident ahead	10
Somewhat	Highly	Immediate 3-10 s	Enter street address number	11
Directly	Little/No	Near Term 10-20 s	Approaching school zone	12
Directly	Moderate	Preparatory 20-120 s	Narrow bridge ahead, slow down	13
Somewhat	Moderate	Emergency 0-3 s	Incoming phone call	14
Somewhat	Moderate	Immediate 3-10 s	Call waiting	15
Directly	Highly	Discretionary > 120 s	ESC disabled	16
Somewhat	Highly	Near Term 10-20 s	Ambulance approaching	17
Directly	Moderate	Discretionary > 120 s	Road may be icy	18
Somewhat	Little/No	Emergency 0-3 s	Testing emergency broadcast signal	19
Directly	Little/No	Preparatory 20-120 s	Fasten seat belt	20
Somewhat	Moderate	Near Term 10-20 s	Activate fog lamps	21
Directly	Little/No	Discretionary > 120 s	Passenger air bag disengaged	22
Not	Highly	Emergency 0-3 s	Stay back 50 ft from snowplow	23
Somewhat	Little/No	Immediate 3-10 s	Watch for deer next 1 mile	24
Not	Highly	Immediate 3-10 s	Pay toll, 500 ft	25
Somewhat	Highly	Preparatory 20-120 s	Dense fog ahead	26
Somewhat	Little/No	Near Term 10-20 s	Approaching drunk driver checkpoint	27
Somewhat	Highly	Discretionary > 120 s	Rear defrost on	28
Somewhat	Moderate	Preparatory 20-120 s	Recalculating navigation route	29
Not	Moderate	Emergency 0-3 s	CD error	30
Not	Highly	Near Term 10-20 s	Exit freeway next right	31
Not	Moderate	Immediate 3-10 s	Cruise activated	32
Somewhat	Moderate	Discretionary > 120 s	Headlamp out	33
Somewhat	Little/No	Preparatory 20-120 s	Tune to 1590 AM for traffic information	34
Not	Moderate	Near Term 10-20 s	Left lane closed, 1 mile	35
Somewhat	Little/No	Discretionary > 120 s	1 missed call for John Doe	36
Not	Little/No	Emergency 0-3 s	Be caller 4 and win free movie tickets	37
Not	Highly	Preparatory 20-120 s	High engine temperature	38
Not	Highly	Discretionary >120 s	Low oil pressure	39
Not	Moderate	Preparatory 20-120 s	Toll ahead, $1	40
Not	Little/No	Immediate 3-10 s	Incoming text message	41
Not	Moderate	Discretionary > 120 s	Rest area, 5 miles	42
Not	Little/No	Near Term 10-20 s	Load CD	43
Not	Little/No	Preparatory 20-120 s	Car wash next right	44
Not	Little/No	Discretionary > 120 s	Low wiper fluid	45

however, interruptions can be costly to the processing of information. An experiment examining interruption of a continuous control and tracking task with discrete matching tasks indicated that people strategically postpone interruptions until they finish a task [23]. Similarly, an experiment investigating discrete tasks interrupted by tracking tasks and screen-blanking periods

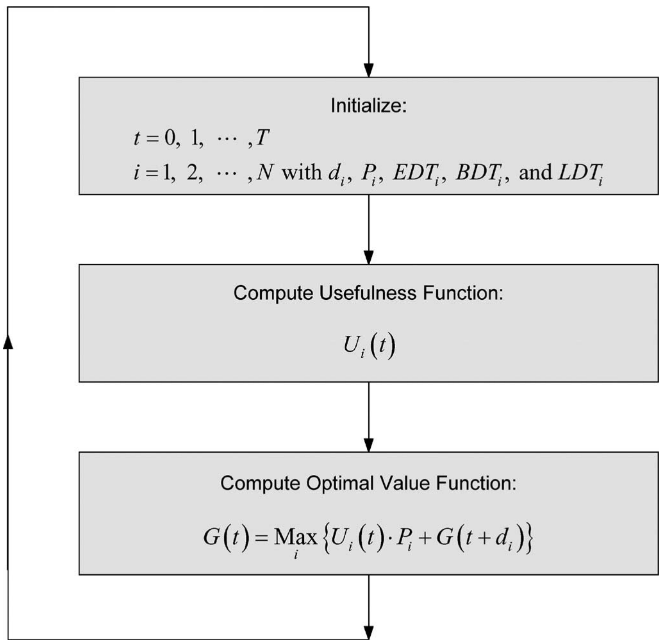

Fig. 1. DP model framework.

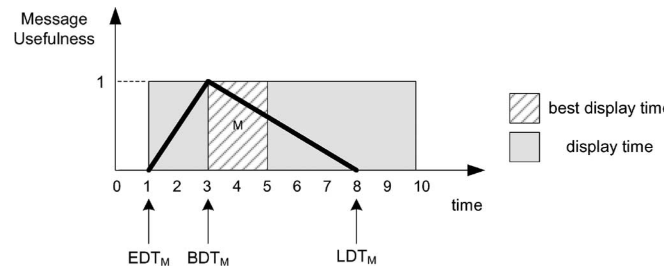

Fig. 2. Shape of a triangular distribution for message usefulness.

found that the greatest cost to resuming a task resulted from midtask interruptions [24]. Thus, the DP model developed here will assume that a message, if displayed, must be displayed without interruption for the required duration. Furthermore, the algorithm will allow a message to be displayed more than once if it still has value after it is first displayed. The basic idea underlying the DP model is shown in Fig. 1.

A. Initialization

Consider a set of messages $i = 1, 2, \ldots, N$, each with a duration d_i, a priority P_i, and a function $U_i(t)$, which specifies its relative usefulness if its display begins at time t. Note that a high value of the priority of message i, i.e., P_i, indicates high priority (e.g., $P_i > P_j$ means that message i has priority over message j). In other words, this is the reverse of the POI of SAE, for which a small value indicates higher priority. The benefit of message i is displayed at time t is assumed to be the product of the usefulness function $U_i(t)$ and the relative priority of the message P_i. Also, we assume that there is no positive reward for early message display, message display is a memoryless process, and there are no precedence constraints among the messages.

In this paper, it is assumed that each message i has the following:

1) "best display time" (BDT_i), at which it is most useful (i.e., $U_i(\mathrm{BDT}_i) = 1$);
2) earliest display time (EDT_i), before which the message will not be useful (i.e., $t \leq \mathrm{EDT}_i \Rightarrow U_i(t) = 0$);
3) latest display time (LDT_i), after which the message will not be useful (i.e., $\mathrm{LDT}_i \leq t \Rightarrow U_i(t) = 0$).

Ideally, a simple algorithm could be used to specify BDT, EDT, and LDT based on the characteristics of each message. Unfortunately, this is not possible. Instead, the values depend on the specific content of the message and the required response of the driver. Some messages concern strategic responses of drivers, such as the decision to exit the freeway for food. Others concern tactical responses, such as changing lanes for a work zone. Others concern operational responses, such as maintaining a set speed and lane position. The time constants for each of these general classes of behavior are quite different; thus, the difference between the earliest and latest possible presentation times will be correspondingly different. The time constant for operational control is on the order of 1 s, that for tactical control is 10 s, and that for strategic control is 100 s [25]–[27]. Considering only the simple distinction of operational, tactical, and strategic control, the difference between the earliest and latest message presentation times might vary between 0.75 and 2 s for operational control but between 1 and 3 min for strategic control.

Beyond the timing considerations associated with operational, tactical, and strategic control, the specific values of the earliest, latest, and best presentation times depend on the specific response required by the driver. For messages concerning the roadway, the latest display time would be based on the response time of the driver and the proximity to the roadway hazard. At the operational level, the response time for a driver to begin braking is approximately 1.5 s [28]–[30]. This response time and the event dynamics can determine the latest message presentation time [31]. The earliest display time should occur slightly before the driver can confirm the message with the information from the roadway; otherwise, drivers may not trust the accuracy of the information [32]. When such confirmatory information is not available or is available only after the best display time, the earliest display time should be defined according to the slowest response process that is likely to occur. These somewhat vague constraints on message display timing reflect the challenge of developing a generic algorithm to define presentation times. The values of safety relevance, operational relevance, and time urgency of the SAE standard for message priority were determined through a consensus process of driving safety experts. The values of the earliest, best, and latest display times may require a similar process [16].

B. Usefulness Function

We assume that the usefulness of each message has a *triangular distribution*. In Fig. 2, the usefulness of Message M is 0 at both the earliest time for the beginning of display (EDT_M) and the latest time for the beginning of display (LDT_M) on the screen and a maximum value of 1 at the best time for the beginning of display (BDT_M). A solid bar shows the range during which a message can be displayed, and the best display time is highlighted. That is, in the most desirable scenario, Message M is displayed from time $t = 3$ to time $t = 5$. Since the given duration of the message display is 2, we know that the latest time for the beginning of the message is time $t = 8$ so that the latest time that the message can be on display is time $t = 10$.

Thus, the following equation is used to determine the usefulness of message i at time t:

$$U_i(t) = \begin{cases} 0, & \text{if } t = \mathrm{EDT}_i \\ \frac{t - \mathrm{EDT}_i}{\mathrm{BDT}_i - \mathrm{EDT}_i}, & \text{if } \mathrm{EDT}_i < t < \mathrm{BDT}_i \\ 1, & \text{if } t = \mathrm{BDT}_i \\ \frac{t - \mathrm{BDT}_i}{\mathrm{LDT}_i - \mathrm{BDT}_i}, & \text{if } \mathrm{BDT}_i < t < \mathrm{LDT}_i \\ 0, & \text{if } t = \mathrm{LDT}_i. \end{cases} \tag{1}$$

Note that the assumption of a triangular utility function is for the purpose of illustration. Any other function might be used to specify message usefulness. We further assume that time may be discretized, with $t = 1, 2, \ldots, T$, to define the *planning horizon*.

We begin by defining a renewal point as the time at which the IVIS becomes available to display a message. We assume a memoryless system in which decisions made at a renewal point do not depend on any decisions made prior to that time.

C. Recursive Definition of the Optimal Value Function

We now define the optimal value function $G(t)$, i.e., the maximum possible total benefit from time t until the end of the planning horizon T, given that t and T are both renewal points.

The optimal value function may recursively be defined as

$$G(t) = \operatorname*{Max}_i \left\{U_i(t) \cdot P_i + G(t + d_i)\right\}. \tag{2}$$

That is, if message i is selected for display at a renewal point t, then $t + d_i$ becomes the next renewal point, and the total benefit will be the sum of the benefit of message i and the maximum possible benefit from time $t + d_i$ to time T. The following example illustrates the DP modeling and analysis approach.

III. Illustrative Example of the Computational Method

Suppose there are $N = 15$ messages to be displayed. The characteristics of these messages are shown in Table III. P is the priority, and *Duration* is the processing time, which includes the response duration (i.e., the time needed to respond to a message). EDT, BDT, and LDT are the earliest, best, and latest times for beginning the display of each message, respectively.

Notice that a dummy or "idle" message has been defined since we assume that the screen need not continually display messages. Fig. 3 shows the corresponding Gantt diagram, with a bar showing the range during which a message can be displayed and the "best" display time.

Assuming that the usefulness U of each message has a *triangular distribution*, we can define $U(t)$ for each message during the interval $[0, T]$, where $T \geq 20$, using (1). When this value is then multiplied by the priority P, the benefit is obtained. For

TABLE III
MESSAGE CHARACTERISTICS

Message ID	*P*	*EDT*	*BDT*	*LDT*	*Duration*
Message 1	45	5	12	13	3
Message 2	38	13	14	18	2
Message 3	37	2	7	9	3
Message 4	31	11	11	14	3
Message 5	30	5	16	18	2
Message 6	23	7	9	11	2
Message 7	22	7	8	11	3
Message 8	20	1	3	4	3
Message 9	19	1	9	13	3
Message 10	17	4	12	13	3
Message 11	16	0	5	12	3
Message 12	12	0	1	10	3
Message 13	9	0	5	9	2
Message 14	5	12	17	18	2
Message 15	4	0	2	7	2
Idle	0	0	0	20	1

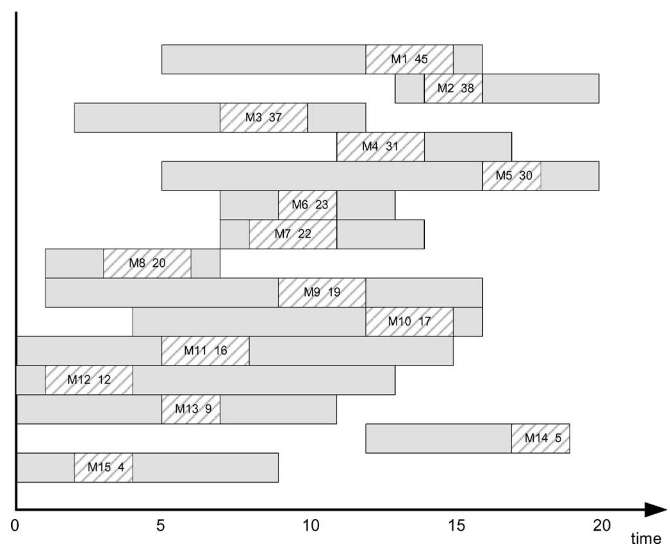

Fig. 3. Graphical representation of the IVIS message characteristics.

example, 22.2 is the benefit of Message 3 at time $t = 5$, which is defined by the product of 37 $(= P_3)$ and 0.6 $[= U_3(5)]$.

Consider, for example, the recursive computation at time $t = 1$ (see Table IV). The recursive computation of the optimal value function G using (2) begins with the boundary condition $G(20) = 0$ and proceeds through $G(t)$, $t = 19, 18, \ldots, 1$, producing the values shown in Table V. Suppose Message 12 is selected to be displayed on the screen, ending at time $t = 4$. Then, the total benefit would be 178.4, i.e., 12 (the benefit of Message 12) plus 166.4 (the future value that we can get from Message 13 from the result of the previous calculation at time $t = 4$ in Table V). If, on the other hand, we do not select any messages to display (i.e., idle message is presented until time $t = 2$), then there is no benefit. Calculating the benefit for time $t = 2$ in Table IV, we find that we can achieve a maximum benefit value of 179.2. Thus, the total benefit at time $t = 1$ would be 179.2. However, the optimal decision at time $t = 1$ is to display Message 15, ending at time $t = 3$. The corresponding benefit $G(1)$ would be 181.2, i.e., 2 (the benefit of Message 15)

TABLE IV
RECURSIVE COMPUTATION AT TIME $t = 1$

Message ID	*P*	*EDT*	*BDT*	*LDT*	*Duration*
Message 1	45	5	12	13	3
Message 2	38	13	14	18	2
Message 3	37	2	7	9	3
Message 4	31	11	11	14	3
Message 5	30	5	16	18	2
Message 6	23	7	9	11	2
Message 7	22	7	8	11	3
Message 8	20	1	3	4	3
Message 9	19	1	9	13	3
Message 10	17	4	12	13	3
Message 11	16	0	5	12	3
Message 12	12	0	1	10	3
Message 13	9	0	5	9	2
Message 14	5	12	17	18	2
Message 15	4	0	2	7	2
Idle	0	0	0	20	1

TABLE V
OPTIMAL ORDERING OF THE MESSAGES

time	*G (t)*	Message ID	Next renewal point
1	181.171	***Message 15***	***3***
2	179.171	Idle	3
3	179.171	***Message 8***	***6***
4	166.371	Message 13	6
5	159.171	Idle	6
6	159.171	***Message 3***	***9***
7	143.571	Message 3	10
8	129.571	Idle	9
9	129.571	***Message 6***	***11***
10	106.571	Idle	11
11	106.571	***Message 1***	***14***
12	88.5	Message 1	15
13	68	Idle	14
14	68	***Message 2***	***16***
15	43.5	Message 2	17
16	30	***Message 5***	***18***
17	15	Message 5	19
18	0	Idle	19
19	0	Idle	20
20	0	Idle	21

plus 179.2 (the future value that we can get from Message 8 from the result of the previous calculation at time $t = 3$ in Table V). That is, $G(1)$ is the value of the total benefit summed from $t = 1$ to $t = 20$.

Based on our computations, the maximum benefit that may be obtained is $G(1) = 181.2$. A "forward pass" is used to identify the optimal schedule, where the total benefit is calculated at each decision point, starting at time 0, and the message whose display provides the greatest total benefit is chosen. In this example, the optimal schedule displays Message 15 with duration 2 at $t = 1$ so that the next renewal point is at $t = 3$. Table V indicates that if $t = 3$ is a renewal point, then Message 8 should be displayed so that the next renewal point occurs at $t = 6$. This process results in the schedule Message 15 → Message 8 → Message 3 → Message 6 → Message 1 → Message 2 → Message 5, after which, at $t = 18$, the display is idle. We note that Message 1, which has the highest P, is displayed earlier than its BDT so that both Message 2 and Message 5 may be displayed at their BDTs, resulting in a greater total benefit. Also, Message 4, which has a relatively high P value, is omitted so that both Message 1 and Message 2 may be displayed, again resulting in a greater total benefit.

Because this example used a simple priority P to illustrate the method, which does not reflect the time urgency of a message of the SAE's POI, it is possible that the SAE criterion might generate a different message sequence than the current example. Thus, to compare the DP algorithm performance to that of the SAE criterion, we consider another example.

IV. Comparison of the DP Model and the SAE Priority Criterion

Suppose $N = 50$ messages are to be displayed. Table VI shows the message characteristics. LDT is the latest time to begin displaying the message on the display screen. Thus, the POI values of each message become lower (i.e., have higher priority) as the renewal point approaches its LDT. As in the previous example, *Duration* is the processing time needed to attend to the message.

In the previous example, the objective function of the DP algorithm was to maximize the total benefit, which was obtained from the product of message priority and message usefulness (i.e., the value of the message over time). In contrast, in this example, the objective function of the DP algorithm is to minimize the average POI weighted by message duration. We assign a POI rank for each message by using the SAE criteria of safety relevance, operational relevance, and time urgency. A "forward pass" is again used to identify the optimal schedule: Message 4 with duration 15 is displayed at $t = 1$ so that the next renewal point is at $t = 16$. Message 24 should be displayed given a renewal point $t = 16$, and so on. Thus, we obtain the schedule Message 4 → Message 24 → Message 48 → Message 31 → Message 31 → Message 34 → Message 35 → Message 48 → Message 40 → Message 48, after which, at $t = 126$, the display is idle. Table VII shows the optimal schedule, in which the total POI of messages displayed is 54 and the weighted average POI is 4.44.

To implement the SAE criterion, we use the greedy algorithm. Every message is sorted by POI rank, and when the display becomes available, the POI of each message is recomputed. The message having the smallest POI (highest priority) at that instant is chosen without considering the effect of postponing competing messages. Table VIII shows the schedule resulting from the SAE criterion in which the display is idle at $t = 131$. The corresponding total POI is 34, and the weighted average POI is 4.65.

According to Tables VII and VIII, the DP algorithm generates a schedule that provides a smaller value of the weighted average POI. At $t = 31$, for example, the SAE criterion chooses

TABLE VI
MESSAGE CHARACTERISTICS

Message ID	Safety Index	Operational Index	*LDT*	*Duration*	Message ID	Safety Index	Operational Index	*LDT*	*Duration*
1	2	1	1	15	26	3	2	18	25
2	2	2	1	25	27	1	2	19	20
3	3	2	1	5	28	3	2	25	5
4	1	1	2	15	29	2	2	35	20
5	1	2	2	10	30	2	1	40	15
6	1	3	2	25	31	1	3	50	5
7	2	3	2	10	32	3	1	55	20
8	3	1	2	10	33	2	1	65	20
9	3	2	2	20	34	1	1	70	20
10	3	3	2	5	35	1	2	75	15
11	2	3	4	15	36	3	3	78	10
12	1	3	5	30	37	1	3	80	5
13	3	1	5	25	38	2	3	85	15
14	2	1	6	10	39	3	1	95	15
15	1	1	7	20	40	1	1	100	20
16	3	3	7	5	41	1	2	110	15
17	1	2	8	15	42	3	3	121	5
18	2	2	9	15	43	1	2	123	20
19	2	1	13	15	44	1	3	123	20
20	3	1	13	10	45	2	1	123	30
21	1	3	15	5	46	2	3	123	15
22	3	3	15	20	47	3	1	124	10
23	2	3	17	15	48	1	1	125	10
24	1	1	18	15	49	2	2	125	15
25	2	2	18	15	50	3	2	125	15

TABLE VII
SCHEDULES PRODUCED BY THE DP AND SAE ALGORITHMS

Time	DP Algorithm			SAE Algorithm		
	Message ID	*POI*	*Duration*	Message ID	*POI*	*Duration*
1	4	1	15	4	1	15
16	24	1	15	24	1	15
31	48	10	10	34	10	20
41	31	9	5			
46	31	9	5			
51	34	6	20	34	6	20
71	35	4	15	35	4	15
86	48	10	10	40	6	20
96	40	2	20			
106				41	4	15
116	48	2	10			
121				48	2	10

TABLE VIII
SCHEDULE FROM THE SAE CRITERION

Time	Message ID	*POI*	*Duration*
1	4	1	15
16	24	1	15
31	34	10	20
51	34	6	20
71	35	4	15
86	40	6	20
106	41	4	15
121	48	2	10

Message 34 since it has the smallest POI value at that instant. However, the DP algorithm considers the effect of postponing Message 34 and chooses Message 48, which does not lead to discarding vital information like Message 31. At $t = 86$, Message 40 has the smallest POI value. Thus, the SAE criterion chooses it at that instant. However, the DP algorithm considers the effect of postponing Message 40 and chooses Message 48 so that both messages may be displayed, as both have a relatively high priority (i.e., a lower POI value). A single message (i.e., Message 41) is sacrificed, however. By doing this, eventually, the smaller value of the weighted average POI is obtained from the DP algorithm. Therefore, we may conclude that for a unit period of time, the DP algorithm provides drivers with a more valuable set of messages, as defined by the POI metric, compared with the SAE criterion. This indicates that the DP algorithm produces potentially better and arguably more appropriate timing of messages compared to the SAE formulation.

V. Conclusion

IVISs have the potential to improve road safety by ensuring that drivers receive accurate and timely information. However, as indicated by the ISO and SAE standards for message prioritization, researchers and designers also acknowledge the potential for poorly managed messages to undermine driving safety.

The ISO and SAE standards consider message priority, operational relevance, and time urgency; however, neither of these methods considers the value of messages over time. An optimization algorithm that is based on a recursive DP technique offers a promising approach to managing message presentation. This approach considers the time-dependent value of messages neglected by other approaches. Both the simplicity and benefits of this approach have been shown in the two examples. The proposed DP algorithm generates substantially improved message sequences compared to SAE criterion. This is achieved by considering the time constraints that govern the value of a message and the message priority, whereas the SAE criterion produces only simple priority-based schedules.

The proposed algorithm assumes a known set of messages to be displayed over a fixed time horizon; it may be used in a dynamic setting, in which additional messages are added to the set by simply recomputing the schedule. That is, additional messages may arrive before the completion of the computed schedule, in which case, the schedule may be revised, beginning at the next renewal point (i.e., the end of the message currently being displayed). This is easily accommodated because, as shown in our example, the proposed algorithm requires minimal computation and is scalable.

This paper provides a way of ordering the presentation of messages over time to avoid overwhelming the driver with information. It is anticipated that the proposed DP model will enhance the benefits of intelligent transportation systems.

VI. Future Considerations

The algorithm assumes a triangular distribution for message usefulness U_i, in which the value of displaying a message at $t = \text{EDT} = \text{LDT}$ is 0 and at $t = \text{BDT}$ is 1. Messages may follow different distributions, such as those whose maximum value occurs when they are first generated and whose value drops to zero at a specific point in time. Therefore, alternate distributions, such as a trapezoidal distribution, may need to be considered in fine tuning this algorithm.

More importantly, the model assumes no precedence constraint among the messages and that the system is memoryless. These two assumptions hold for many messages, but not for systems that deliver a coordinated sequence of messages, such as those associated with route guidance. With route guidance, messages have clear precedence relationships associated with the order of maneuvers. The temporal separation of route guidance commands due to the distance between turns makes it unlikely that the proposed algorithm would generate messages different from one that includes precedence information.

The memoryless property of the algorithm is also consistent with most, but not all, message sequences that a driver might receive. In most situations, the presentation of a message would not need to influence the timing of subsequent messages. One exception to this would be situations in which a logical grouping of messages might make drivers more able to understand and respond to the messages as a group rather than as separate messages. Information with regard to services offered at a freeway exit is one example of this. Here, the timing of messages might benefit from a consideration of what has just been presented so that messages could be clustered to make the driver understand what is offered at a particular exit. Just as with route guidance, it is likely that the timing constraints will cluster such messages, although the algorithm assumes a memoryless process. However, this may not be the case for all such situations, and the message description and algorithm may need to be extended to accommodate such situations. One way to extend the algorithm is to adjust the EDT, BDT, and LDT according to the display of other messages.

The algorithm also assumes that messages, once displayed, are displayed without interruption. The algorithm also allowed for messages to be displayed more than once if they remained useful. In the driving domain, there is the potential for time- and safety-critical messages (e.g., imminent collision ahead) to arise while a lower priority message (e.g., low wiper fluid) is being displayed. These critical messages must immediately be displayed to benefit the driver and are only relevant in the current situation. Therefore, future applications of this method should address circumstances where a message must be interrupted to present a higher priority message. Such an algorithm must balance the psychological cost of interruption with the benefit associated with attending to the interrupting message [33].

The increasing prevalence of IVISs make it increasingly likely that drivers could be overwhelmed by a sequence of poorly prioritized messages. Our DP algorithm begins to address this issue. Even an ideally timed sequence of messages could overwhelm the driver if the messages coincide with demanding driving maneuvers, such as negotiating a merge onto a freeway. The DP algorithm could address this possibility by treating these maneuvers as "messages" that merit the driver's attention and accordingly schedule other messages, diminishing the possibility that IVISs will distract drivers from critical driving demands.

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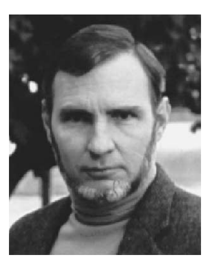
Hansuk Sohn received the B.A. degree in industrial engineering from Sung-Kyun-Kwan University, Seoul, Korea, in 1992 and the M.S. and Ph.D. degrees in industrial engineering from the University of Iowa, Iowa City, in 1995 and 2004, respectively.

He is currently an Assistant Professor with the Department of Industrial Engineering, New Mexico State University, Las Cruces. His research interests focus on the study of large-scale computational science and engineering, which includes the implementation of decomposition techniques to optimize integer programming, stochastic programming, and dynamic programming. His specific applications of interests include network design, logistics, and supply chain management.

John D. Lee received the B.A. degree in psychology and the B.S. degree in mechanical engineering from Lehigh University, Bethlehem, PA, in 1987 and 1988, respectively, and the M.S. degree in mechanical engineering and the Ph.D. degree from the University of Illinois, Urbana-Champaign, in 1989 and 1992, respectively.

He is currently a Professor with the Department of Mechanical and Industrial Engineering, University of Iowa, Iowa City, and is the Director of Human Factors Research at the National Advanced Driving Simulator. He is also affiliated with the Department of Neurology, the Public Policy Center, the Injury Prevention Research Center, and the Center for Computer-Aided Design. His research focuses on the safety and acceptance of complex human–machine systems by considering how technology mediates attention. His specific research interests include trust in technology, advanced driver-assistance systems, and driver distraction.



Dennis L. Bricker received the B.S. and M.S. degrees in mathematics from the University of Illinois, Urbana-Champaign, in 1965 and 1966, respectively, and the M.S. and Ph.D. degrees in industrial engineering and management science from Northwestern University, Chicago, IL, in 1972 and 1975, respectively.

He is a Professor Emeritus with the Department of Mechanical and Industrial Engineering, University of Iowa, Iowa City, where he has taught and conducted research on operations research, with a primary interest in optimization algorithms and applications.

Joshua D. Hoffman received the B.S.E. and M.S. degrees in industrial engineering from the University of Iowa, Iowa City, in 2003 and 2004, respectively. He is currently working toward the Ph.D. degree with the Department of Mechanical and Industrial Engineering, University of Iowa, where he conducts research for the Center for Computer-Aided Design.

His research interests include understanding driver distraction caused by in-vehicle technologies, modeling driver behavior, and human monitoring of intelligent autonomous systems.