Development of an Adaptive Workload Management System using Queueing Network-Model of Human Processor

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Drivers overloaded with information from in-vehicle systems significantly increase the chance of vehicle crashes. Developing adaptive workload management systems (AWMS) to dynamically control the rate of messages from these in-vehicle systems is one of the solutions to this problem. However, existing AWMS do not use a model of the driver to estimate workload and only suppress or redirect messages without changing the rate of messages from the in-vehicle systems. In this work, we propose a prototype of a new adaptive workload management system (QN-MHP AWMS) which includes: a model of driver workload based on the queueing network theory of human performance (Liu, 1996, 1997; Liu, Feyen, and Tsimhoni, 2006) estimating driver workload in different driving situations, and a message controller dynamically controlling the rate of messages presented to drivers. Corresponding experimental studies were conducted to validate the potential effectiveness of this system in reducing driver workload and improving driver performance.

1. INTRODUCTION

Multitasking between driving and using in-vehicle information systems may impose high information load on drivers, increasing drivers’ mental workload (e.g., Alm & Nilsson, 1995) which in turn increases the chance of vehicle collisions comparing to a single driving condition (Violanti & Marshall, 1996).

Recently, several adaptive workload management systems have been developed to reduce driver mental workload via the design and use of adaptive workload management systems (AWMS) (Piechulla, et al., 2003) (See Table 1 and also review in Green, 2004). There are two important aspects of these adaptive workload management systems which need further improvements: First, at the human end, a model of driver cognitive system might be useful in these systems so that drivers’ workload can be estimated in multitasking situations. Second, at the system end, the all-or-none solution (suppressing or redirecting messages) might be too simple and a more general solution might be to treat the delay between messages as a continuous variable whose value is set depending on different driving situations. (see a review by Haigney & Westerman 2001, discussing effects of concurrent mobile phone use on driving).

In this work, we first propose a new adaptive workload management system (QN-MHP AWMS) which includes: a model of driver workload to estimate driver workload based on research in cognitive modeling; b) a message controller which dynamically controls the rate of messages in various driving situations. Second, we describe the model of driver workload and how it can be used to simulate driver workload and performance in a typical multitasking situation in driving. Third, corresponding experimental study to validate the potential effectiveness of this system in reducing the driver workload is described.

2. DESIGNING THE PROTOTYPE OF QN-MHP ADAPTIVE WORKLOAD MANAGEMENT SYSTEM

The purpose of QN-MHP adaptive workload management system (QN-MHP AWMS) is to regulate the rate of messages from the in-vehicle system based on driving condition and properties of the secondary task, so that the drivers’ workload will be reduced effectively. Figure 1 shows a prototype of the adaptive system which is composed of two parts: QN-MHP and a message controller (MC). QN-MHP AWMS receives three types of information: 1) driving conditions (e.g., current driving speed and curvatures); 2) properties of messages from in-vehicle systems (processing time at the perception, cognitive and motor part); 3) properties of driver (e.g., age and level of driving experience). QN-MHP simulates the driver workload and performance, and the message controller regulates the rate of messages in real time and outputs the messages to the driver based on the optimal rate derived from the simulation results.

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Table 1. Summary of four major adaptive workload management systems (AWMS)

<table>
<thead>
<tr>
<th>Existing AWMS</th>
<th>Human Model Used</th>
<th>Dual Task (2nd Task’s Property)</th>
<th>Message Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Phone Adaptive System</td>
<td>No</td>
<td>Single (Not considered)</td>
<td>Redirect to a phone mailbox only</td>
</tr>
<tr>
<td>(BMW, Germany) (Piechulla, et al., 2003)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Voice Adaptive System</td>
<td>No</td>
<td>Single (Not considered)</td>
<td>Suppress only</td>
</tr>
<tr>
<td>(Toyota, Japan) (Uchiyama et al., 2004)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. SaveIt Adaptive System</td>
<td>Under Development</td>
<td>Under Development</td>
<td></td>
</tr>
<tr>
<td>(Delphi, 2004-2007)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. In-Vehicle Message System</td>
<td>No</td>
<td>Single (Not considered)</td>
<td>Wait for driver’s response only</td>
</tr>
<tr>
<td>(Leeds, UK) (Jamson, et al., 2004)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the current study, we focus on testing the potential effectiveness of AWMS in reducing driver workload and improving performance when driving conditions (speeds and curves) change. The optimal delays of messages in different driving conditions were obtained by running the simulation model of QN-MHP offline (see Sections 4); based on these optimal delays, a simulated message controller in the experiment dynamically sets the delay in real time according to the current driving condition (see Section 5).

3. AN EXAMPLE OF MULTITASKING IN DRIVING

As a practical example of multitasking in driving, we chose to model a police vehicle with two tasks: 1) Speeding detection: officers read from an in-vehicle radar display on the dashboard the speed and distance to a target vehicle. Whether the target vehicle is speeding is determined by a combination of the speed and distance. For example, on a road with speed limit 55 miles/hr, 65 miles/hr and above is considered speeding, 55 miles/hr and below is not speeding, and between 56 and 64 miles/hr is considered speeding only if the distance is below 100. 2) Radio message response task: Messages received by the officers usually come from multiple resources (headquarters, other police officers, and maintenance), and the officers need to respond to higher priority messages (e.g., headquarters) by pressing a button on the radio.

4. QUEUING NETWORK MODELING OF HUMAN PERFORMANCE AND MENTAL WORKLOAD

Along the line of research on developing unified theories of cognition advocated by Newell (1990), we have been making steady progress in developing a queuing network architecture for human performance modeling called the Queuing Network-Model Human Processor (QN-MHP) (Liu, Feyen, and Tsimhoni, 2006). The model has been applied to quantify human performance in a variety of tasks including simple and choice reaction time (Feyen, 2002), transcription typing (Wu & Liu, 2004a), and others.

Besides modeling human performance in these tasks, QN-MHP is also used to account for the indexes of mental workload: subjective workload rating measured by NASA-TLX (Wu & Liu, 2006b).

Multitasking Simulation using QN-MHP

To model driver workload and performance, the input to the model was modified so that it can represent: 1) a road with two levels of curvature (straight and curves of 250 meter radius); 2) driving speed (45 and 65 miles/hr). The task analysis of driving task was described in the work of Liu et al., (2006) in detail.

Simulation Results

The total length of road driven by the model was 5,000 meters in each run (the model performed 6 runs with different standard random number series in the Promodel software). By changing the delay (inter-arrival time between the messages in the secondary task), simulation results of workload, standard deviation of lane positions and reaction time of the secondary task were obtained. Figures 2 and 3 show the simulation results of overall workload, and delta overall workload ($\Delta$Workload = Workload$\text{delay}_i$ - Workload$\text{delay}_{i-1}$, delay$_1$=3, delay$_2$=5, delay$_3$=10, delay$_4$=15, delay$_5$=20, and delay$_6$=30).

The optimal delay of messages was defined as a delay time that an increase of delay produces at least a decrease of one major unit in the workload scale (i.e., 10, in the 0-100 workload rating, this is an arbitrary definition of optimal delay which can be changed by the user of the system depending on different workload situations, see discussion section). Accordingly, based on Figures 2 and 3, the differential threshold in decreasing workload is set at 10 (See the straight line in Figure 3); therefore, the following minimal delay time are suggested for the four driving conditions: 65 curve: Delay$\geq$15 sec; 65 straight: Delay$\geq$10 sec; 45 curve: Delay$\geq$10 sec; 45 straight: Delay$\geq$5 sec.
Figure 2. Simulated overall workload using QN-MHP

Figure 3. Simulated delta overall workload (Workload\_{delay i} - Workload\_{delay i-1})

Figure 6. Simulated average reaction time of the secondary task

Similar analysis was obtained for SD of lateral position and for secondary task performance. Combining the three lists of suggestions we derived the following suggestions of the minimal delays for the four driving conditions when a driver is performing the secondary task: 65 curve: Delay $\geq$ 15 sec; 65 straight: Delay $\geq$ 10 sec; 45 curve: Delay $\geq$ 10 sec; 45 straight: Delay $\geq$ 5 sec.

5. EXPERIMENTAL STUDIES OF THE PROTOTYPE OF QN-MHP AWMS

The potential effectiveness of the adaptive system was tested using two conditions. 1) Adaptive condition: between the four driving conditions (two speeds × two curvatures), delay time was set based on the optimal rates derived from the simulation results of QN-MHP. Within each driving condition, this delay time was kept constant. 2) Random condition: across the four driving conditions, the delay time was set based on the random number function in Excel; this delay time was constant within each driving condition. The total amount of stimuli, i.e., the total number of radio messages and the amount of radar detection results, was the same in the two conditions.

Experimental Design and Implementation

A one-factor within-subject design was used in this experiment. The independent variable was the two conditions of the system (random vs. adaptive) and dependent variables were the driver workload measured by NASA-TLX, standard deviation of lane position and performance of the secondary task. Each participant used two conditions of the system (adaptive and random) combined with four levels of driving conditions (speed: 45 and 65 miles/hr; curvature: 250m and straight). Order was counterbalanced across participants.

Participants, Equipment and Test Materials. Six licensed drivers participated in this experiment (3 men and 3 women, age 25-33 years, mean=29). All participants had corrected far (20/40) and midrange (80 cm, 20/70) visual acuity or better.

This experiment was conducted using the UMTRI Driver Interface Research Simulator (See Figure 7). The simulated roads had two levels of road curvature (straight sections, curves of 250 m radius sections) and speed-limit signs (45 and 65 miles/hr) were placed in each section (straight and curve). A 12” touch screen was mounted on the right of the driver at arm’s length (see Figure 8).

52 95
SPEEDING

Message Controller. The Wizard of OZ method was used to simulate the message controller in QN-MHP AWMS. The experimenter obtained current speed and curvature from the simulator and selected optimal message rates based on the model’s suggestion list (the experimenter had more than 100 practices on this selection process and the duration of this selection process was less than 2 sec with no selection errors).

Experimental Task and Procedure. 1) Driving Task: Participants were instructed to drive in the right lane and maintain a speed following the speed-limit signs on the simulated roads. If they drove 5 miles/hr above or below the speed shown on the speed-limit signs, they were prompted by a computer-generated message. 2) Secondary Task: The secondary task was composed of two subtasks simulating the typical multitasking scenario: In the first subtask participants were instructed to press the “H” button on the touch screen (See Figure 8) and then speak aloud “In route” once they heard the word “Headquarter” from the speakers. If they heard “Maintenance”, they did not need to make a response. The second subtask was a speeding judgment task: participants were asked to judge whether other vehicles were speeding or not based on the two numbers on the touch screen (see Figure 8) following the three rules described in Section 4. If participants judged that the other car was speeding they were instructed to press the “SPEEDING” button on the touch screen. During the experiment, the stimuli of the two subtasks in the secondary task were presented to a participant in a serial order (e.g., a radio-message followed by numbers of the radar system or another radio-message). The duration between stimuli was called delay time, manipulated in the adaptive and random condition. The ratio of each subtask in the secondary task throughout the experiment was 50%.

Experimental Results

Subjective Workload. Figure 9 shows the comparison of overall workload and workload in the six subscales in NASA-TLX between the random and adaptive conditions. Compared
to the random condition, the overall workload was significantly reduced, $F(1,5)$=12.91, $p<.01$. T test revealed a significant difference of overall workload between the random and adaptive condition, $t(10)$=3.36, $p<.01$. Because of the relative small sample size ($n=6$), Kruskal-Wallis Test, one of non-parametric tests, was used to test the significant differences between the two conditions, Chi-square=7.11, df=1, $p<.01$.

Among the six subscales/dimensions of NASA-TLX, significant differences between the random and adaptive condition were found on the TD (Temporal Demand) and FR (Frustration) dimensions.

2) Performance in Driving and Secondary Task

The adaptive system also reduced the standard deviation of lane positions as one of major indexes of driving performance (see Figure 10) ($F(1,5)$=9.91, $p<.05$; $t(10)$=3.15, $p<.05$; Kruskal-Wallis Test, Chi-square=8.37, df=1, $p<.01$).

Figure 11 shows the comparison of reaction time of the secondary task between the random and adaptive condition (error rate of the secondary task is less than 1% in both conditions). The simulated adaptive system also reduced the reaction time of the secondary task as one of performance indexes of mental workload in driving ($F(1,5)$=9.11, $p<.05$; $t(10)$=3.15, $p<.05$; Kruskal-Wallis Test, Chi-square=8.37, df=1, $p<.01$).

6. DISCUSSION

To reduce driver workload in multitasking, a prototype of a new adaptive workload management system (QN-MHP AWMS) was developed in this work. The experimental study validated the potential effectiveness of the system in reducing workload. Driving performance and secondary task performance were also improved.

QN-MHP AWMS may provide a useful tool for in-vehicle system designers to estimate driver workload when drivers are manipulating different user interfaces of in-vehicle systems. Furthermore, the simulation results of QN-MHP and the suggested optimal message rates can be approximated by relatively simple algorithms which can be implemented into microcomputer in vehicles. The message controller simulated in this experiment can also be easily replaced by software which reads information of the vehicle speed and angles of the steering wheel from the data bus line in each vehicle.

The current work only tested the adaptive part of QN-MHP AWMS depending on different driving conditions, future simulation and experimental studies are expected to add driver properties (e.g., age, driving experience, gender) into the simulation and empirical validations of the system. Previous published work of QN-MHP has considered aging factor (variable $A$ in Equations 2-7 in Wu & Liu, 2006b, 2006c) as one of the major factors in predicting driver workload.

In summary, we are extending the current approach both in modeling different tasks in driving and applying the model in designing intelligent in-vehicle systems to improve transportation safety.

Reference


