Distraction Beyond the Driver: Predicting the Effects of In-Vehicle Interaction on Surrounding Traffic

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ABSTRACT
Recent studies of driver distraction have reported a number of detrimental effects of in-vehicle interaction on driver performance. This paper examines and predicts the potential effects of such interaction on other vehicles around the driver’s vehicle. Specifically, the paper describes how computational cognitive models can be used to predict the complex interactions among several vehicles driving in a line when one or more of the vehicles’ drivers are performing a secondary task (phone dialing). The results of simulating two distinct car-following scenarios illustrate that in-vehicle interaction by one driver can have significant downstream effects on other drivers, especially with respect to speed deviations relative to a lead vehicle. This work generalizes recent work developing computational evaluation tools for user interfaces in complex domains, and further serves as an example of how user interaction in some domains can have broader effects on the community at large.

Author Keywords
Driving; driver distraction; multitasking; cognitive models.

ACM Classification Keywords

General Terms
Human Factors, Design

INTRODUCTION
Driver distraction is a critical issue facing the global community today, and the CHI community has recently expended great effort on this problem to understand the effects of in-vehicle interaction [e.g., 6, 7]. The vast majority of work on driver distraction, both within and outside the CHI community, has focused on one driver interacting with the interface and the effects on performance as observed through the driver’s vehicle. However, like many areas of human-computer interaction, driver distraction does not occur in isolation: it can greatly affect those around the driver, to the point at which others may be exposed to dangerous, even life-threatening, situations.

Unfortunately, the empirical basis for understanding the effects of distraction on surrounding traffic is currently very thin. There have been large-scale studies of distraction in terms of the risk factor of a crash [e.g., 4, 8], along with many single-driver studies of distraction [e.g., 3, 6], but very little research focusing on effects on surrounding drivers and vehicles (with just a few exceptions discussed later). However, the recent development of computational tools to simulate behavior and evaluate distraction [e.g., 10] offers great potential to begin understanding this issue. In particular, such tools can be extended to simulate not just one driver-vehicle system, but a fleet of drivers and vehicles, and then to simulate and predict effects when one or more of these drivers is performing a secondary in-vehicle task.

This paper takes this approach as an important first step in understanding the effects of distraction on surrounding traffic. The paper describes a generalization of Distract-R [10], a tool that allows designers to prototype in-vehicle interfaces and then simulate driver interaction with these interfaces to predict potential distraction. Distract-R relies on an underlying computational cognitive model to make psychologically plausible predictions with respect to a person’s cognitive, visual, motor, and multitasking abilities. The system developed here simulates many instances of the model (with some driver variability), one following another in a car-following chain of vehicles. In this way, the system allows for testing of how one driver’s distraction may affect others in the chain. More generally, by demonstrating how multiple models can be simulated together in a unified environment, this work can serve as an example of how to pursue future model-based prototyping and evaluation for any domain with complex interactions among users.

DISTRACT-R AND TRAFFIC SIMULATION
The starting point for this work is the Distract-R system [10] for rapid prototyping and evaluation of in-vehicle interfaces. Distract-R allows a user to (1) prototype a new device with a simple interface, (2) demonstrate tasks that can be performed on the interface, (3) define characteristics of the drivers and scenarios, and (4) simulate drivers performing these tasks to...
predict relevant measures of driver performance (e.g., lateral deviation from the lane center as a measure of steering accuracy). Distract-R incorporates a computational cognitive architecture called ACT-R [1] to provide a psychologically plausible model of driving, and relies on a recent psychological theory of multitasking for predictions of how interface use is interleaved with driving; however, these details are largely “under the hood,” freeing the user to focus on the interfaces and tasks of interest.

The standard Distract-R system focuses on a single driver and thus simulates only that one driver’s behavior (although some scenarios include a simple automated lead vehicle). Prediction of effects on surrounding traffic required an extension of the system to simulate multiple humanlike drivers simultaneously. For this purpose, the open-source Distract-R system was adapted in two major ways.

First, a traffic simulation system was built around the system, such that the system could include many instances of the core driver model. In this way, one humanlike model would follow another, and thus the effects of one driver’s interaction could ripple to the drivers and vehicles following that driver. Two separate scenarios were developed:

1. **Standard car-following scenario.** This scenario included a line of humanlike model drivers, one following the next, on a straight roadway. A simple automated vehicle, driving at a constant speed, was placed at the front of the line to provide a stable basis for following behavior.

2. **Circular car-following scenario.** This scenario used a circular loop of traffic, mimicking a recent experiment designed to illustrate how traffic phenomena can evolve even in simple situations [13]. The scenario includes a line of vehicles, similar to the highway car-following, except that the first vehicle is made to follow the last (with no automated lead vehicle)—creating an “infinite” sequence of models, each following and reacting to the vehicle in front of them.

Figure 1 shows sample visualizations for each scenario.

The second adaptation related to the car-following aspects of the cognitive driver model. The original model used only time headway for speed regulation, which works well at high speeds but unfortunately not at low speeds: as speed approaches zero, any given time headway (say, 1 second) translates to a headway distance approaching zero (i.e., right at the lead vehicle’s bumper). Thus, the model was modified to switch between time-based control at higher speeds and distance-based control at lower speeds (threshold at 18 kph, with a desired following distance of 5 m). The steering parameter that scales the change in headway was multiplied 3 to improve stability and was only factored into control for deceleration (as proposed by [14]). Other relevant parameters remained at the values in the open-source distribution.

Although the concept of cloning the driver model to generate traffic lends psychological plausibility in using a validated model, it assumes that all drivers are exactly the same—thus distorting the attempt to produce a realistic prediction of traffic flow. To remedy this issue, variability was added to the most critical parameter for car-following, namely the desired following time headway: human drivers tend to follow a lead vehicle with a time headway roughly distributed between 1 and 2 seconds [see 2]; to reflect this result, each model driver is given a desired time headway uniformly sampled from the range 1.25 to 1.75 seconds.

The resulting system, which allows rapid prototyping of an interface and then simulation of a traffic environment, is fairly unique in the context of the research literature. On the one hand, there are large-scale traffic simulators to aid transportation engineers in designing efficient roadways, but even so-called “microsimulators” that model individual vehicles [e.g., 5] do not predict drivers’ cognitive and associated behavior, and thus cannot model in-vehicle interaction. On the other hand, there are models of individual drivers that focus on cognition and behavior (see [9] for a review), but do not attempt to account for behavior and traffic beyond the driver’s vehicle. The new traffic-based Distract-R allows a user to prototype a new in-vehicle device interface, and then in seconds, to generate predictions of driver performance and their potential effects on larger-scale traffic patterns.
TEST CASES AND RESULTS

Standard Car-Following

The first test case for the proposed approach examined standard car-following along with a common in-vehicle task, manual phone dialing, which has been shown to be detrimental to driver performance (see [10] for a review). The test case included 16 model-controlled vehicles, one following the other, with an automated lead vehicle driving at a constant speed of 48 kph. The simulation began with the vehicles at a standstill spaced 20 m apart. The lead vehicle slowly accelerated to its final speed, leading each model vehicle to follow and accelerate in turn. Each simulation run lasted 10 minutes of simulated time (needing only a few seconds of real time). Results did not include the first 20 seconds to allow for vehicles to accelerate to full speed.

Results were collected from 10 groups of simulated drivers, in which each group comprised 16 model drivers with randomly sampled values for desired time headway. Each group was then run in three conditions: the 0/16 condition with no distracted drivers, the 1/16 condition with 1 distracted driver (3rd vehicle behind the lead) performing the secondary dialing task, and the 3/16 condition with 3 distracted drivers (3rd, 8th, and 13th vehicles behind the lead).

In the latter two conditions, the vehicles performing the secondary task dialed a phone every 20 seconds during the 10-minute run, roughly simulating an intermittent but still somewhat continual source of distraction. Because each group was run in all three conditions, repeated-measures ANOVAs were used to check for statistical significance (including a Greenhouse-Geisser correction when Mauchly’s test indicated a violation of the sphericity assumption).

Figure 1(a) shows the simulation and significance results across several aggregate measures of traffic and stability; each line in the graphs connects the results for a particular group of model drivers. Significance results were computed using repeated-measure ANOVAs comparing results in the three conditions.

Figure 2: Results for (a) standard car-following and (b) circular car-following. Each graph line represents a group of model drivers simulated across three conditions, namely with 0, 1, or 3 distracted drivers (performing the dialing task) out of 16 total drivers. Significance results were computed using repeated-measure ANOVAs comparing results in the three conditions.
correction) indicated that the 0/16 condition differed significantly from 1/16 and 3/16, p<.05, but these two conditions did not differ from each other. Thus, even a single distracted driver was enough to generate an effect on overall traffic stability as measured by deviations in speed.

Circular Car-Following
The second test case kept most aspects of the previous study, but changed the scenario: the road was a loop and introduced a circular interaction among all the vehicles (this time with no automated pace car—all vehicles were driven by a humanlike model). The 16 vehicles were initially spaced evenly throughout the circular road. All other parameters were kept constant from the first test case.

Table 1(b) shows the results for the circular car-following simulations. Headway distance remained constant (constrained by the loop), but headway deviation grew slightly with 1 or 3 distracted drivers, p<.05. Again, larger effects were observed in the speed-related measures. For mean speed, there was a very significant effect, p<.001, in which speed decreased with more distracted drivers; the 0/16 condition was marginally different from 1/16, p<.10, and significantly different from 3/16, p<.01, and 1/16 was significantly different from 3/16, p<.05. For speed deviation, there was also a very significant effect, p<.001; the difference between 0/16 and 3/16 was the only significant difference in pairwise comparisons, p<.01. As is especially evident for speed deviation, the circular road exhibited greater potential for instability because the effects of traffic bottlenecks wrap around the road circuit.

About Validation
With simulations of human behavior, it is preferable to compare the simulated behavior directly to human behavior. However, there are currently no empirical data sets that make such validation possible here, and one might imagine why: an ideal validation of the 16 humanlike model drivers would require 16 human drivers all driving and interacting at the same time, in the real world or in a simulator. Nevertheless, there is indirect evidence for many of the predictions here. Strayer et al. [12], Kujala [11], and Cooper et al. [3] found that distracted drivers tended to reduce their mean speed; this effect was observed in both test cases here (albeit the effect was very small for standard car-following). Salvucci and Macuga [11] reported an increased speed deviation for phone dialing, which was shown significantly in the simulations. Strayer et al. [12] also found that headway standard deviation increased with distraction, which occurred for the circular (though not the standard) scenario. Cooper et al. [3] and Strayer, Watson, and Drews [12] found that headway distance was not affected by distraction; the straight-road simulations produced a significant but very small effect (.04 m difference between the 0/16 and 3/16 conditions).

DISCUSSION
This paper has shown that it is possible to take an in-vehicle task interface and predict its effects not only on the driver’s vehicle, but also on other drivers and vehicles in surrounding traffic. The use of humanlike models of driver behavior for all vehicles is critical, because it results in psychologically plausible predictions of one driver’s reaction to another. Large-scale traffic simulations [e.g., 5] have been used to predict congestion and even carbon emissions; the driver models used here are much more computationally intensive than those in the large-scale simulators, and thus scaling up to (for example) city-wide traffic presents a challenge in simplifying and optimizing the models. Nevertheless, the current work offers the promise of predicting distraction effects across a broad transportation network—for example, predicting the changes in a city’s traffic patterns if 5% of its drivers are operating a cell phone at any given time.

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