An Investigation of Driver Distraction Near the Tipping Point of Traffic Flow Stability

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Objective: The purpose of this study was to explore the interrelationship between driver distraction and characteristics of driver behavior associated with reduced highway traffic efficiency. **Background:** Research on the three-phase traffic theory and on behavioral driving suggests that a number of characteristics associated with efficient traffic flow may be affected by driver distraction. Previous studies have been limited, however, by the fact that researchers typically do not allow participants to change lanes, nor do they account for the impact of varying traffic states on driving performance. **Methods:** Participants drove in three simulated environments with differing traffic congestion while both using and not using a cell phone. Instructed only to obey the speed limit, participants were allowed to vary driving behaviors, such as those involving forward following distance, speed, and lane-changing frequency. **Results:** Both driver distraction and traffic congestion were found to significantly affect lane change frequency, mean speed, and the likelihood of remaining behind a slower-moving lead vehicle. **Conclusions:** This research suggests that the behavioral profile of "cell phone drivers," which is often described as compensatory, may have far-reaching and unexpected consequences for traffic efficiency. **Application:** By considering the dynamic interplay between characteristics of traffic flow and driver behavior, this research may inform both public policy regarding in-vehicle cell phone use and future investigations of driving behavior.

INTRODUCTION

In the past few decades, traffic delays caused by highway congestion have become a serious problem. As a result, traffic researchers have turned toward identifying and eliminating traffic inefficiencies. One such cause of traffic inefficiency may be driver distraction. Indeed, driver characteristics thought to contribute to efficient traffic flow, such as rapid reaction time, consistent speed, appropriate following distance, and anticipatory visual scanning (Brackstone, McDonald, & Wu,1998; Davis, 2004; Huang, 2002; Kerner, 2004; Knospe, Santen, Schadschneider, & Schreckenberg, 1999, 2002; Treiber, Kesting, & Helbing, 2006a, 2006b), may all show impairment when a driver's attention is diverted toward a secondary task (Beede & Kass, 2006; Horrey & Wickens, 2006; Recarte, & Nunes, 2000; Strayer & Drews, 2004; Törnros & Bolling, 2006). These studies are limited, however, by the fact that the researchers typically did not allow participants to change lanes, and they did not account for the impact of varying traffic congestion on driving performance. Thus, it is not known how distraction affects unconstrained driving performance as traffic density increases toward a congested state.

According to the three-phase traffic theory (Kerner, 2004), the relationship between drivers and traffic can be characterized as a complex system with emergent properties, bidirectional causality, and mutual constraints. From this perspective, the various patterns of traffic flow are determined by driver behaviors (Huang, 2002), and driver behaviors are, in turn, affected by patterns in traffic flow (Treiber et al., 2006b). This research provides a bridge between these levels of organization by investigating the effect

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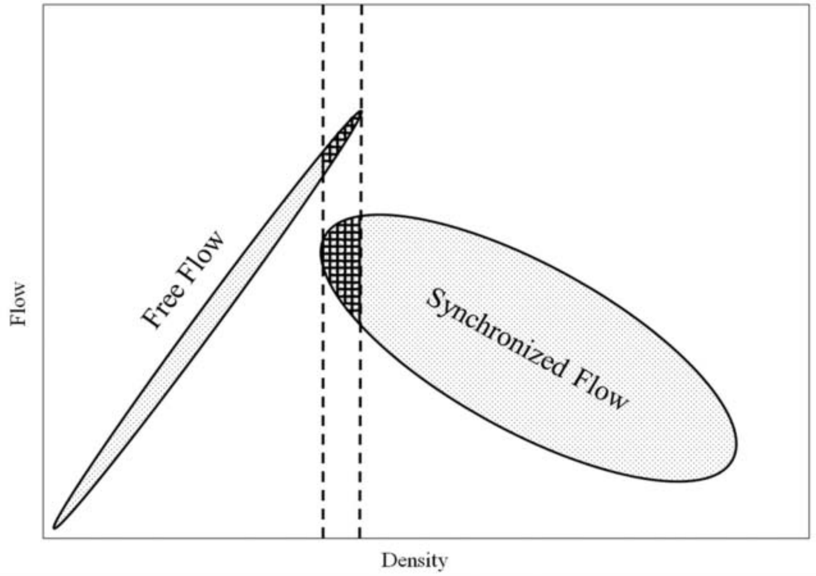

Figure 1. A representation of the three-phase traffic theory, cross-plotting flow and density. Shaded areas represent commonly observed flow–density traffic relationships for both free-flow and synchronized-flow traffic phases. Adapted from "Basis of Three Phase Traffic Theory" by B. Kerner, 2004, in *The Physics of Traffic: Empirical Freeway Pattern Features, Engineering Applications, and Theory*, p. 96, Figure 4.5. Copyright 2004 by Springer-Verlag Berlin Heidelberg. Adapted with kind permission of Springer Science+Business Media.

of various levels of freely flowing traffic on driving behavior while considering the broader implications for traffic that could arise from these driving behaviors.

Driving in Traffic

On a macroscopic level, traffic movement is generally characterized by three interrelated indices of efficiency: flow (i.e., the number of vehicles per hour per lane), density (i.e., the number of cars per mile per lane), and speed (i.e., the average vehicle speed). A generalized representation of the interrelationship between flow and density is shown in Figure 1. This figure illustrates the important finding that some levels of identical highway demand are *bi-stable*, meaning that the same rate of vehicle flow or density can generate two possible flow patterns. This is seen in the two darkly hatched areas, which occur at similar vehicle densities but at different flows. In one case, higher flow rates result from higher average traffic speeds, whereas in the other case, average speeds and flow are reduced. Kerner (2004) suggested that this sudden loss of traffic flow is analogous to a phase transition in thermodynamics, in which the general patterning of highway traffic is rapidly reorganized from one state (e.g., *free flow*) to another (e.g., *synchronized flow*).

In multilane roadways, free-flow traffic is characterized by high, asynchronous speeds in each lane; modest forward following distances; and frequent lane changes (Huang, 2002; Kerner, 2004; Treiber et al., 2006a). These characteristics create flow stability that is robust to a wide variety of traffic perturbations. However, as highway demand increases toward the capacity ceiling, vehicles begin to interact, the stability of free flow is reduced, and even slight variations in driving behaviors could disproportionately affect traffic by causing a premature traffic phase transition (Nagel & Paczuski, 1995). This transition to synchronized flow results in reductions in lane change opportunities, frequent speed fluctuations, reduced speeds, and increased travel time.

Although the precise interrelationship between driver characteristics and the onset of traffic congestion is still debated, a number of factors that contribute to inefficient traffic flow have been identified. In general, highway efficiency is reduced by vehicles that proceed more slowly than surrounding traffic, display greater speed variability, cut off other drivers during a lane change, respond more slowly to sudden-onset events, and exhibit greater-than-necessary time headways (Brackstone et al.,1998; Davis, 2004; Huang, 2002; Kerner, 2004; Knospe et al., 1999, 2002; Treiber et al., 2006a, 2006b).

Although previous research on distracted driving has not investigated the effect of varying traffic characteristics on these measures, a number of studies have reported that distracted drivers exhibit general reductions in average speed (Burns, Parkes, Burton, Smith, & Burch, 2002; Haigney, Taylor, & Westerman, 2000), increased speed variability (Green, Hoekstra, & Williams, 1993; Reed & Green, 1999), delayed response time (Alm & Nilsson, 1995; Strayer & Johnston, 2001), and increases in vehicle following distance (Greenberg et al., 2003; Strayer & Drews, 2004; Strayer, Drews, & Crouch, 2006). In addition, Beede and Kass (2006) found that drivers in a city environment made fewer lane changes when distracted by a secondary task. In this way, the behavior of distracted drivers is consistent with the general characteristics of traffic in the synchronized-flow phase, suggesting that driver distraction may reduce highway efficiency by hastening the onset, or increasing the duration, of synchronized traffic flow.

The Current Research

The aim of the current research was to explore the influence of a secondary task on unconstrained driving behavior in three levels of freely flowing traffic. Although there are many forms of driver distraction, a cell phone conversation was used because of the prevalence of in-vehicle cell phone use. This research was guided by the hypothesis that in freely flowing traffic, in-vehicle cell phone conversations would elicit driving behaviors consistent with broad traffic characteristics in the synchronized-flow phase. To explore this hypothesis, we allowed drivers to freely change lanes and proceed at their own pace, restricted only by the speed limit and behavior of surrounding vehicles.

Figure 2. A typical participant conversing on a hands-free cell phone in a three-lane section of the high-flow driving scenario.

Consistent with Beede and Kass (2006), who studied lane-changing behavior in a city environment, we reasoned that concurrent cell phone conversation would cause a reduction in lane changes. In addition, we predicted that lane-change frequency would indicate an inverse *U*–shaped function as density increased (Huang, 2002). With respect to the quality of lane-changing maneuvers, we expected that the widely studied perceptual deficits associated with in-vehicle cell phone conversation (McCarley et al., 2004; Strayer, Cooper, & Drews, 2004) would result in poorer lane changes, possibly leading to increased instances of cutting off other vehicles. Additionally, we expected that drivers on a cell phone would increase their following distance relative to leading vehicles. Finally, on the basis of previous findings, we expected that drivers on a cell phone would reduce their speed across all levels of traffic congestion.

METHOD

Participants

Thirty-six undergraduates from a local university participated in the research (mean age 21.5 years). All had normal or corrected-to-normal visual acuity and a valid driver's license.

Stimuli and Apparatus

A PatrolSim (manufactured by L3 communications) high-fidelity fixed-base driving simulator, illustrated in Figure 2, was used in the study. The simulator incorporates proprietary vehicle dynamics with traffic scenario and road surface software to provide realistic scenes and traffic conditions. The dashboard instrumentation, steering wheel, gas pedal, and brake pedal were taken from a Ford Crown Victoria® sedan with an automatic transmission.

The highway database simulated a 38.6-km (24-mile) multilane roadway with on- and off-ramps, overpasses, and two- and three-lane traffic in each direction. Three unique driving scenarios, 14.8 km (9.2 miles) in length, were created from this database. Each 14.8-km (9.2-mile) scenario began with a 6.3-km (3.9-mile) stretch of two-lane traffic in each direction, followed by 8.5 km (5.3 miles) of three lanes of traffic in each direction. A large, grassy median separated the two directions of traffic.

The traffic flow, speed, and model of simulated vehicles differed in each scenario. Traffic in the low-, medium-, and high-flow scenarios was calibrated to 1,450, 1,850, and 2,250 vehicles per hour per lane, respectively, and consisted of approximately 10% heavy vehicles (semi trucks, dump trucks, etc.). Traffic speed in the low-flow driving condition fluctuated between 96.5 km/h and 112.7 km/h (between 60 mph and 70 mph) with a mean speed of 103 km/h (64 mph). Traffic speed for the medium-flow condition fluctuated between 72.4 km/h and 88.5 km/h (between 45 mph and 55 mph) with a mean speed of 80.5 km/h (50 mph).Traffic speed in the high-flow condition fluctuated between 64.4 km/h and 80.5 km/h (between 40 mph and 50 mph) with a mean speed of 69.2 km/h (43 mph). These parameters were targeted to reflect actual traffic conditions recorded by traffic-monitoring stations on a major interstate in the western United States.

Procedure

Upon arrival, participants completed a questionnaire assessing their interest in potential topics of cell phone conversation. Participants were then familiarized with the driving simulator using a standardized 20-min adaptation sequence, after which the data collection began.

Participants drove each of the three scenarios in both single- and dual-task conditions, resulting in six driving performance observations, a 3 (traffic flow) × 2 (distraction) repeated-measures design. The order of scenario presentation and conversation condition was counterbalanced. Participants were instructed to drive as they normally would during a typical highway situation. They were informed that they were free to change lanes and were reminded to use their turn signals.

The dual-task condition involved naturalistic conversation with a confederate via cell phone. Once initiated, conversation was allowed to progress and develop naturally. In the cases in which natural conversation was not sufficient to maintain a constant exchange, the confederate generated additional dialogue based on the participant's questionnaire. To avoid any possible interference from manual components of cell phone use, participants used a hands-free cell phone that was positioned and adjusted before driving began. Additionally, the call was initiated before participants began the dual-task scenarios and lasted until scenario completion.

Dependent Measures

The dependent measures that were collected and analyzed for this research included the following: *Lane change frequency* was defined as the number of instances participants exited their lane and fully entered an adjacent lane. *Lag distance* was defined as the distance in meters between the center of the participant's vehicle and the center of the nearest following vehicle located in the selected lane during a lane change. Lag distance was assessed once participants fully entered an adjacent lane and only for vehicles within the following/not-following threshold of 60 m. *Following ratio* was defined as the percentage of each drive that a participant's vehicle was less than 60 m from a leading vehicle in the same lane. *Forward following distance* was defined as the distance in meters from the center of the participant's vehicle to the center of the nearest lead vehicle in the same lane, measured only when the participant's vehicle was within 60 m of a lead vehicle. *Driving speed* was defined as the mean of a participant's speed in miles per hour.

RESULTS

With the exception of lag distance, each of the dependent measures was analyzed using a 3 × 2 repeated-measures general linear model. All p values for the distraction comparisons were divided by 2 to account for the directionality of our hypotheses. Multiple planned comparisons

TABLE 1: Driving Performance Variables for Single- and Dual-Task Conditions by Traffic Flow

	Low Flow		Medium Flow		High Flow	
Dependent Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*
Lane change frequency						
Single task	4.50	3.30	7.90	3.70	7.50	4.30
Dual task	4.80	3.50	6.30	3.50	6.10	2.70
Following ratio						
Single task	0.20	0.13	0.37	0.14	0.46	0.13
Dual task	0.26	0.14	0.42	0.12	0.52	0.11
Forward following distance (m)						
Single task	35.60	8.94	30.40	4.51	27.70	3.97
Dual task	35.50	7.31	30.80	5.20	27.70	3.93
Driving speed (km/h)						
Single task	110.60	4.00	95.80	8.00	79.80	8.90
Dual task	110.90	6.40	92.20	8.00	77.10	6.90

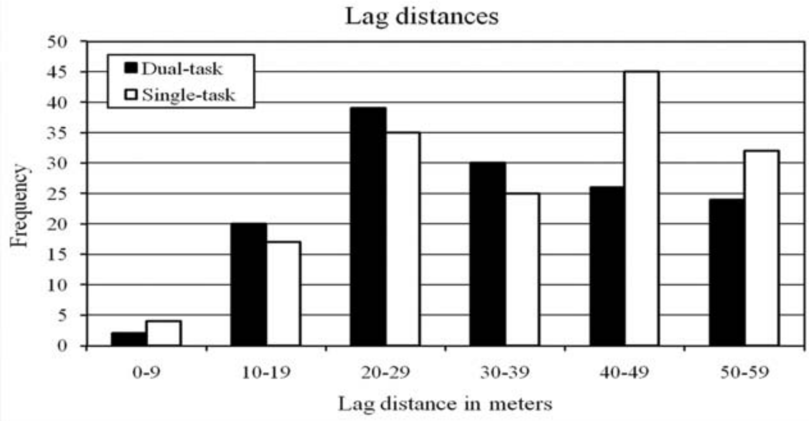

Figure 3. A grouped frequency chart of lag gaps for lane change maneuvers in the low-, medium-, and high-flow highway driving conditions.

were then used to assess the effects of distraction at each level of traffic flow. The results of these comparisons are in Table 1.

Preliminary analysis of lag distance indicated that the majority of drivers often changed lanes with greater than 60 m between them and a following vehicle, and a minority frequently changed lanes with less than 60 m of lag distance. Because the average lag distance did not capture this meaningful variation, we elected instead to include in a chi-square analysis each lane change leaving less than 60 m of lag distance.

Lane Change Frequency

An overall analysis of lane-change frequency found that it was significantly reduced by the distraction condition, $F(1, 35) = 3.78$, $p < .05$, and traffic flow, $F(2, 70) = 17.96$, $p < .001$; however, the interaction between flow and distraction was not significant, $F(3, 105) = 2.96$, $p > .05$. Additional analyses indicated that when drivers conversed on the phone, they made fewer lane changes in the medium-flow, $t(35) = 2.91$, $p < .01$, and high-flow conditions,

$t(35) = 1.76$, $p < .05$, whereas the distraction condition had no effect on lane change frequency in the low-flow condition, $t(35) = .34$, $p > .05$.

Lag Distance

Drivers changed lanes with less than 60 m of lag distance 299 times. Of those, 158 occurred in the single-task condition and 141 in the dual-task condition. Figure 3 indicates that lane changes leaving less than 40 m of lag distance were more common for drivers in the dual-task condition, and lane changes leaving between 40 m and 60 m of lag distance were more common for drivers in the single-task condition, $\chi^2(1) = 5.37$, $p < .05$. Overall, when conversing on a cell phone, drivers were 11% more likely to change lanes with less than 40 m of lag space.

Following Ratio

Compared with the single-task condition, drivers on cell phones spent more time following within 60 m of a lead vehicle, $F(1, 35) = 11.43$, $p < .001$. Post hoc comparisons revealed that these differences were significant in the low-flow, $t(35) = 2.76$, $p < .01$, medium-flow, $t(35) = 1.73$, $p < .05$, and high-flow, $t(35) = 1.96$, $p < .05$, conditions. Not surprisingly, drivers spent significantly more time following a leading vehicle as traffic flow increased, $F(2, 70) = 140.46$, $p < .001$; however, the interaction between traffic flow and distraction was not significant, $F < 1$.

Forward Following Distance

As expected, forward following distance decreased as traffic flow increased, $F(2, 70) = 42.22$, $p < .001$. However, contrary to our expectations, forward following distance was not affected by distraction, $F < 1$, and likewise, the interaction between traffic flow and distraction was not significant, $F < 1$.

Driving Speed

Driving speed was significantly reduced as traffic flow increased and average speeds decreased, $F(2, 70) = 384.4$, $p < .001$. In addition, mean speed for drivers in the dual-task condition was significantly lower than for drivers in the single-task condition, $F(1, 35) = 4.73$, $p < .05$. This difference appeared to be independent of traffic flow, as the interaction between traffic flow and distraction was not significant, $F(3, 105) = 2.36$, $p > .05$. Post hoc comparisons indicated that the driving speeds under single- and dual-task conditions were significantly different for the medium-flow, $t(35) = 1.94$, $p < .05$, and high-flow conditions, $t(35) = 1.88$, $p < .05$, whereas no effect of distraction on speed was observed in the low-flow driving condition, $t(35) = -.49$, $p > .05$.

Additional analyses of speed indicated that mean speed for drivers on cell phones did not differ when drivers were either following, $F(1, 35) = 0.04$, $p > .05$, or not following a lead vehicle, $F(1, 35) = 0.56$, $p > .05$. This finding suggests that drivers in the single-task condition maintained slightly higher speeds than did drivers conversing on cell phones by selecting lanes with less congestion.

DISCUSSION

The purpose of this study was to explore the interrelationship between driver distraction and characteristics of driver behavior associated with reduced traffic flow. The speed and spacing of scenario vehicles were designed to probe driving behavior in a range of traffic situations representative of the free-flow phase in Kerner's (2004) three-phase traffic theory. This research was guided by the overarching hypothesis that in freely flowing traffic, distraction from a secondary task would elicit driving behaviors that are consistent with the reduced traffic efficiency of synchronized flow.

On the basis of previous investigations, we expected that drivers on cell phones would exhibit the following: a reduction in lane changes, an inverse *U*–shaped distribution of lane change frequency across the three flow conditions, poorer lane changes, an increase in forward following distance, and a reduction in mean driving speed. Results were largely consistent with these original hypotheses; however, two findings were unexpected.

First, with the exception of following ratio, driving in the low-flow condition did not appear to be affected by concurrent cell phone conversation. We attribute this finding to the fact that average traffic speeds in the low-flow scenario were very high and near the posted scenario speed limit. This may have set a performance ceiling that was easily attainable irrespective of secondary task demand. In some respects, this finding is consistent with findings by Strayer, Drews, and Johnston (2003), who reported that the addition of surrounding traffic was needed to observe an impact of cell phone conversations on driving.

Second, drivers on cell phones did not maintain greater forward following distances. We attribute this finding to the stability of traffic speeds and the ability of drivers to freely vary their lane position. In other research, forward following distance is often recorded using a car-following paradigm in which drivers are instructed to remain behind a lead vehicle without passing (Strayer et al., 2006). Participants were then commonly exposed to frequent and unpredictable braking events designed to simulate stop-and-go traffic and to collect brake reaction time. The speed variability introduced by frequent braking events may differentially affect drivers in single- and dual-task conditions. This conjecture merits further exploration, as the general tendency for drivers to increase forward following distance in the face of increased lead vehicle variability has been suggested as a primary determinant of a phase transition from free to synchronized flow (Treiber et al., 2006a).

Notably, research by Rosenbloom (2006) that did not require drivers to follow a lead vehicle or respond to frequent and unpredictable braking events found that cell phone conversation actually *decreased* forward following distances. These findings suggest that when one removes the constraint to follow a lead vehicle, the increases in forward following distance often reported for distracted drivers may be situational and not characteristic of distracted driving in general.

In the medium- and high-flow conditions, drivers on the cell phone made fewer lane changes than did drivers in the single-task condition. On one hand, this may be construed as a benefit to safety, as changing lanes has been cited as one of the factors most frequently involved in highway accidents (Jeffcoate, Skelton, & Smeed, 1970; Pande & Abdel-Aty, 2006). On the other hand, drivers' ability to change lanes counteracts the tendency of the slowest driver to dominate flow (Chowdhury, Wolf, & Schreckenberg, 1997; Sparman, 1979). Nonetheless, the analysis of lag distance suggests that distraction led to less safe lane changes. Thus, any benefit to safety that may have been gained by making fewer lane changes in the dual-task condition appears to have been offset by the quality of those lane changes.

CONCLUSION

Single- and dual-task performance differences observed in this investigation provide support for the hypothesis that driver distraction leads to driving behaviors associated with congested traffic. In the medium- and high-flow scenarios, a number of driving measures were sensitive to in-vehicle cell phone conversation even though drivers were free to change lanes and to proceed at their own pace. These findings suggest that near the tipping point of traffic stability, the effect of driver distraction may not be isolated to the distracted driver but could have far-reaching and unexpected consequences for traffic flow. Given that an estimated 10% of drivers are conversing on a cell phone during a typical daylight moment (Glassbrenner, 2005), the overall impact of cell phone use on traffic flow could be substantial.

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