Drivers’ Lane Changing Behavior While Conversing On a Cell Phone in a Variable Density Simulated Highway Environment

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ABSTRACT

This research examined the effect of naturalistic, hands-free, cell phone conversation on driver’s lane-changing behavior. Thirty-six undergraduate psychology students drove six 9.2-mile scenarios, in a simulated highway environment, with three levels of traffic density. Participants were instructed only to obey the speed limit and to signal when making a lane change. These simple driving instructions allowed participants to freely vary driving behaviors such as following distance, speed, and lane-changing maneuvers. Results indicated that, when drivers conversed on the cell phone, they made fewer lane changes, had a lower overall mean speed, and a significant increase in travel time in the medium and high density driving conditions. Drivers on the cell phone were also much more likely to remain behind a slower moving lead vehicle than drivers in single-task condition. No effect of cell phone conversation on following distance was observed. Possible implications on traffic flow characteristics are discussed.
INTRODUCTION
In the last few decades, traffic delays caused by freeway congestion have become a serious problem. For pragmatic reasons, efforts to alleviate congestion purely through highway expansion are no longer acceptable; as a result, traffic engineers have turned toward identifying, and eliminating, any possible traffic inefficiencies. Surprisingly, one such inefficiency may be the use of in-vehicle cell phones. Research suggests that many critical components involved in traffic flow such as individual following distance, speed, and acceleration/deceleration profiles differ when drivers are conversing on a cell phone. However, differences in lane changing behavior, which may also affect traffic efficiency, have not been assessed. Furthermore, the current misalignment between output variables provided by behavioral research, and input variables required for micro-simulations, make it difficult to estimate the impact of in-vehicle cell phone conversation on traffic flow. Therefore, the current research aims to assess the impact of in-vehicle cell phone conversation on lane changing behavior in a manner that affords integration with traffic micro-simulation.

Distracted Driving
The concurrent performance of a secondary task that is unrelated to the primary task of driving can be considered a distraction. Types of driver distraction vary from listening to an audio broadcast to interaction with in-vehicle technologies. According to the Cellular Telecommunications and Internet Association (CTIA) the number of wireless phone subscribers in the US increased by 600% from 1995 to 2006 (1). More than 240 million people now use wireless services. A Nationwide Insurance survey estimated that the percentage of wireless subscribers who admit to using their phone while driving is as high as 73% (2). Additionally, the National Occupant Protection Use Survey found that, during a typical daylight moment in 2005, approximately 10% of drivers were using wireless phones in some manner (3).

Convergent findings suggest that when drivers converse on a cell phone they are more likely to be involved in an accident (4,5,6) and generally show a different driving profile than non-distracted drivers (5, 7, 8). A number of reports have found that when conversing on a cell phone drivers adopt increased time headways to traffic and reduce speed (7, 8, 9) although this finding is not universal (10). Furthermore, epidemiological studies suggest that drivers on the cell phone are up to four times more likely to be involved in an accident (4,6). In fact, the relative risk of being involved in a traffic accident while conversing on a cell phone is estimated to be as high as driving while legally intoxicated at a blood alcohol content (BAC) of 0.08 (4, 5). However, unlike the influence of alcohol, which can be measured at the scene of an accident, the role of distraction in an accident may be impossible to establish. Thus, although many researchers have found that cell phones alter driving characteristics, findings appear to be sensitive to the particular research methodology and are not always consistent (e.g. (10,11)).

In response to the rapid increase of in-vehicle cell phone use, 50 countries have adopted laws that mandate a hands-free device for in-vehicle phone conversation (12). However, research has demonstrated that once conversation is initiated, hands-free devices may fail to eliminate the distraction effect (13,14). Thus, the majority of current regulation appears to be misguided and is unlikely to eliminate the distraction effect.

Potential Impact of Distracted Driving on Traffic Flow
Although the effects of in-vehicle cell phone conversation on safety are well documented, the influence on traffic efficiency has not been explored. Changes in driving profiles, such as an increase in reaction time and an increase in following distance, should have a negative impact on traffic flow. The relationship between distracted driving and traffic flow can be inferred from research presented by Strayer and Drews (7). Figure 1, derived from Strayer and Drews, graphically presents a typical sequence of events in a car-following process for drivers both on the cell phone (dual-task) and off the cell phone (single-task).
FIGURE 1 Car-following behavior from a physical driver simulator.

The main findings from Figure 1 can be summarized in two statements: (1) drivers on the cell phone take 17% more time to recover 50% of their speed lost after braking, compared to single-task condition, and (2) following distance in dual-task condition is 12% greater than in single-task. The shaded areas between the curves represent the plausible deterioration in the status of traffic efficiency (which traffic engineers identify as Level of Service). While these differences in driver profiles may have little negative impact for a single driver, on a macroscopic level, the behavioral profile of multiple distracted drivers could lead to dramatic differences in traffic flow characteristics. Traditionally, macroscopic models of traffic flow simply express flow as a function of speed and density \((15, 16)\); nonetheless, recent empirical evidence suggests that driver characteristics such as age and gender may influence this flow-density relationship \((17)\). Additionally, there is some suggestion that traffic density may alter driver behavior \((18)\).

On a more detailed, microscopic level, the movement of individual vehicles on the freeways is described by car-following and lane-changing theories. Car-following theory considers spacing between vehicles and speeds of individual vehicles \((19, 20, 21)\). Lane-changing models consider human perception of surrounding vehicles (distances between vehicles in front and behind the observed vehicle in both current and desired lanes, and speeds of surrounding vehicles).

Research on naturalistic lane-change behavior \((22)\) shows that the most common (55%) reason for a lane-change is the desire to pass a slower lead vehicle, which, when executed safely and efficiently, will have a beneficial impact on traffic flow. However, in order to collect speed and following characteristics, drivers are often explicitly instructed to follow a lead vehicle and not to pass. Thus, from the current literature, it is not clear whether the ability to change lanes while conversing on a cell phone alters car-following characteristics. Moreover, the effect of cell phone conversation on lane-changing behavior is unknown.

With regard to traffic flow, each lane-changing maneuver can cause an increase or decrease in traffic delays depending on the efficiency of the maneuver \((23)\). For instance, if a vehicle \(i\) moves to the faster lane, and does not estimate appropriately the speed of the vehicle \(j\) behind it in the desired (faster) lane and/or distance between them, vehicle \(j\) will be forced to slow down. Consequentially, this deceleration would propagate to other vehicles behind vehicle \(j\), increasing delays. On the other hand, the speed of vehicle \(i\) could be limited by a slow-moving lead vehicle \(k\). By changing lane, vehicle \(i\) would benefit from moving to a more freely flowing lane and, more importantly, allow other vehicles to safely overtake the slow-moving vehicle \(k\); thus increasing the flow of traffic. Additionally, if vehicle \(i\) did not change lanes, following vehicles would have to overtake two slow-moving vehicles and the queue behind vehicle \(k\) would increase over time.

Although the impact of inappropriate lane changes on issues relating to safety and perturbations to traffic is beyond the scope of this paper, many aspects of lane-changing behavior such as lane change frequency, signal usage, and the influence of lane changes on single-vehicle travel time, will be explored.
Current Research
The impact of distraction on traffic flow could be investigated in a number of ways. One possibility might include the integration of physical driving simulation with traffic micro-simulation. Such an integration would feed real-time driver inputs into a micro-simulation environment, allowing the assessment of driver behavior on traffic flow characteristics, likewise, the complex algorithms used in the traffic micro-simulator would provide local traffic behavior in the physical driving simulator. At least one group of researchers has attempted to integrate these two simulation technologies through real-time networking (results of the effort were limited, however, by available technology and computing power) (24). An immediately attainable solution can be achieved through the careful design of physical simulation studies that take into account key characteristics of traffic micro-simulation. One shortcoming of previous research is that it often fails to specify traffic conditions in sufficient detail for integration with micro-simulation. Furthermore, variable traffic density has not previously been considered an important factor for driver assessment, but may interact with in-vehicle distractions. Thus, using available technology, this research aims to characterize behavior of drivers distracted by cell-phone conversation in a naturalistic and precise manner for future implementation in micro-simulation traffic research.

Lane-changing behavior is investigated under three levels of congestion, each representing carefully modeled levels of flow and speed. To investigate naturalistic lane-changing behavior, drivers were allowed to freely change lanes and proceed at their own pace, restricted only by the speed limit and surrounding vehicles.

Nationwide, traffic flow during peak hours varies considerably. In order to capture this variation, we selected three levels of congestion. Table 1 presents these three traffic conditions along with flow and speed information. While the lowest level of traffic density may still be considered congested, it represents the upper limit of free flowing traffic without considerable slowing.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Flow (vehicles/hour/lane)</th>
<th>Speed (miles/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Density</td>
<td>1450</td>
<td>60-70</td>
</tr>
<tr>
<td>Medium Density</td>
<td>1750</td>
<td>45-55</td>
</tr>
<tr>
<td>High Density</td>
<td>2150</td>
<td>40-50</td>
</tr>
</tbody>
</table>

The current research is supported by two hypotheses:
1. In-vehicle cell phone conversation reduces the likelihood of changing lanes, resulting in increased travel time.
2. Traffic density impacts the frequency of lane changing maneuvers.

METHOD AND PROCEDURES

Participants
Thirty-six undergraduates from the University of Utah participated in the research (mean age 21.5). All had normal or corrected-to-normal visual acuity and a valid driver’s license.

Stimuli and Apparatus
A PatrolSim 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, and brake pedal were taken from a Ford Crown Victoria® sedan with an automatic transmission.
The road database simulated a 24-mile multi-lane beltway with on and off-ramps, overpasses, and two- and three-lane traffic in each direction. Three unique driving scenarios, 9.2 miles in length, were created from this database. Each 9.2 mile scenario began with a 3.9 mile stretch of two-lane traffic in each direction, followed by 5.3 miles of three-lanes of traffic in each direction. A large grassy median separated the two directions of traffic. Driving scenarios differed in terms of traffic flow, speed, and vehicle models. Traffic flow was set to 1450, 1750, and 2150 vehicles/hour/lane for each of the driving conditions. Traffic speed in the low density driving condition fluctuated between 60 and 70 mph with a mean traffic speed of 64.4 mph. Traffic speed for the medium density condition fluctuated between 45 and 55 mph with a mean speed of 49.5 mph, while traffic speed in the high density condition fluctuated between 40 and 50 mph with a mean speed of 43.5 mph. Traffic speed and flow were targeted to reflect speed and flow fluctuations on Interstate 15 (I-15) in the Salt Lake City, Utah, metropolitan region (traffic data was taken from Traffic Monitoring Stations along the I-15). These three driving conditions are hereby referred to as low, medium, and high density conditions.

Procedure
Upon arrival, participants completed a questionnaire assessing their interest in potential topics of cell phone conversation. Subjects were then familiarized with the driving simulator, using a standardized 20-minute adaptation sequence, after which the data collection began. Subjects drove each of the three scenarios in both single- and dual-task conditions, resulting in six driving performance observations for each subject. The order of scenario presentation and conversation condition was counterbalanced across participants. Subjects were instructed to drive as they normally would during a typical freeway situation. Subjects were informed that they were free to change lanes and reminded to use their turn signals.

The dual-task condition involved naturalistic conversation on a hands-free cell phone with a confederate (cf. Figure 2). Once initiated, conversation was allowed to progress and develop naturally. In the cases where natural conversation flow was not sufficient to maintain a constant exchange, the research confederate was instructed to generate additional dialogue from the pre-experimental topic-of-interest 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 Variables
Driving variables collected and analyzed for this research included:

- Lane-Change Frequency, defined as the number of instances when a subject left their current lane, fully entering an adjacent lane;
- Signal Count, defined as the number of times that participants activated the turn signal in preparation for a lane change;
- Time Following and Not Following a lead vehicle, defined as the time the lead vehicle position was either less than or greater than 60 meters from the participant vehicle (the following cutoff of 60 meters was based on the composite distribution of following distances);
- Driving Speed, defined as the mean and standard deviations of participant vehicle speed;
Follow Speed, defined as the mean and standard deviation of speed of drivers when following within 60 meters of a lead vehicle;
Non-Follow Speed, defined as the mean and standard deviation of speed for drivers when not following a lead vehicle; and
Travel Time Saved, defined as the difference in the time it took participants to complete each 9.2-mile scenario from the mean travel time for each scenario assuming no lane changes. Mean travel time without lane changes was computed by averaging together travel time for all possible lane combinations in the two and three lane sections for each level of traffic flow. Without changing lanes participants could have traveled 2 x 3 possible paths in each condition generating 6 possible paths that were averaged together to form a travel time baseline.

RESULTS
A directional ANOVA found that lane change frequency was significantly impacted by conversation, $F(1, 34) = 3.78, p < .05$, and density, $F(2, 33) = 22.80, p < .000$; see Figure 3. Further analysis indicated that, when drivers conversed on the phone, they made 21% fewer lane changes in the medium density condition, $t(35) = 2.91, p < .01$, and 19% fewer lane changes in the high density conditions, $t(35) = 1.76, p < .05$. Compared to single-task condition, drivers on the cell phone spent 31%, 16%, and 12% more time following a slower lead vehicle in the low, $t(35) = 2.53, p < .01$, medium, $t(35) = 1.73, p < .05$, and high, $t(35) = 1.88, p < .05$, density scenarios, respectively. Conversely, drivers in single-task condition spent more time overall not following a slower lead vehicle, $F(1, 34) = 7.71, p < .001$. See Figures 4a and 4b.

![FIGURE 3](image-url) Number of lane changes in single- and dual-task for the three traffic densities; error bars represent confidence intervals.
Increased lane-change frequency led to a significant decrease in travel time in the medium and high density conditions (medium, \( t(35) = 1.729, p < .05 \); high, \( t(35) = 1.44, p < .05 \)); see Figure 5a. As expected, this lead to an overall increase in the mean driving speed of participants in single-task condition, \( F(1, 34) = 4.73, p < .05 \); see Figure 5b. Mean speed did not, however, differ between conversation conditions when drivers where either following, \( F(1, 34) = 0.04, p > .05 \), or not following a lead vehicle, \( F(1, 34) = 0.56, p > .05 \).

![Figure 4: Time spent following and not following in single- and dual-task for each traffic density; error bars represent confidence intervals.](image1)

![Figure 5: Travel time saved and mean speed in single- and dual-task for the three traffic densities; error bars represent confidence intervals.](image2)
Following distance decreased as traffic density increased \((F(2, 33) = 42.22, p < .00)\), however, somewhat counter to previous research, following distance was not affected by cell phone conversation \((F(1, 35) = .03, p > .05)\).

Turn signal usage when changing lanes was very good for drivers both on and off the cell phone. Drivers in all experimental conditions averaged slightly more than one signal per lane change which did not significantly differ by conversation condition \((F(1, 34) = .626, p > .05)\), or flow \((F(2, 33) = .925, p > .05)\), suggesting that drivers occasionally indicated a desire to change lanes by activating the turn signal without actually changing lanes. Drivers on the cell phone were no more, or less, likely to use their signals when making a lane change than drivers in single-task condition in the low, \(t(35) = .30, p > .05\), medium, \(t(35) = -1.21, p > .05\), or high, \(t(35) = -1.18, p > .05\), density conditions.

**DISCUSSION**

Lane-changing behavior observed in this research can be summarized by three main findings. First, changing lanes significantly reduced the time needed to drive each 9.2 mile scenario. Second, lane-change maneuvers were significantly more common in the medium and high density conditions than the low density condition. Third, when drivers conversed on the phone, they were less likely to change lanes in both the medium and high density conditions.

By changing lanes, drivers were able to reduce travel time by up to 90 seconds during a 9.2-mile drive in the medium density scenarios and, more importantly, drivers in single-task condition finished the medium and high density scenarios 15 and 19 seconds faster than drivers conversing on the phone. Jointly considered with baseline travel times, these results indicate that drivers on the cell phone took 2.3% and 2.7% longer to complete the medium and high density scenarios respectively. Considered in isolation, these figures may not be sufficient to dramatically alter traffic flow, however, when coupled with other observed characteristics of the distracted driver such as reductions in brake reaction time, changes in acceleration/deceleration profiles, and modifications to following behavior in braking situations, the effect of distraction on traffic flow could be substantial.

This research also found that overall mean driving speed was lower when drivers conversed on a cell phone. However, cell phone conversation did not impact driver speed when either following or not following a lead vehicle; likewise, when drivers were within 60 meters of a lead vehicle, cell phone conversation had no effect on following distance. Nevertheless, when drivers conversed on the cell phone, they spent significantly more time behind slower moving lead vehicles. This indicates that the overall speed decrease for drivers on the cell phone was a direct result of their increased reluctance to change from the slower to the faster lanes.

Previous research has indicated that, when drivers converse on a cell phone, they tend to follow somewhat farther behind a leading vehicle \((7,8,9)\). This pattern was not seen in the current research. There are at least two possible explanations for this. First, following distance is often recorded using a car-following paradigm, where drivers are instructed to remain behind a lead vehicle and not to pass; it is possible that drivers adopt a different strategy when overtaking is not an option. Second, previous car-following research commonly exposes participants to frequent and unpredictable braking events designed to simulate stop-and-go traffic and to collect brake reaction time. The current research did not use a periodically braking lead vehicle. So, it is possible that workload demands in dual-task condition were low enough that drivers on the cell phone did not need to compensate by increasing following distance. Nevertheless, when drivers conversed on the cell phone, they spent significantly more time behind slower moving lead vehicles. This indicates that the overall speed decrease for drivers on the cell phone was a direct result of their increased reluctance to change from the slower to the faster lanes.

From the current study one might be tempted to conclude that the observed reduction in lane changes by drivers conversing on a cell phone could *benefit* traffic flow and reduce accidents during lane-change maneuvers. Such a conclusion rests on the assumption that the quality of lane changes does not differ with cell phone conversation, which may or may not be true. Research that has assessed driver gap estimation and acceptance while distracted has generally found a negative effect of distraction on these types of perceptual decision making \((25, 26)\). Because perceptual judgments differ when drivers converse on a cell phone, it seems reasonable to assume that lane-change quality would also be affected by cell phone conversation. Unfortunately, the design of this research did not allow us to directly assess whether the quality of lane-change maneuvers differed when drivers were conversing on a phone. A follow-up study could assess this dimension of lane changing.

The results from this research suggest that both traffic flow characteristics and driver distraction affect lane-changing behavior. Overall, this research found that by making fewer lane changes drivers on the cell phone significantly increased overall travel time. Given that 10% of drivers are conversing on a cell phone during a typical daylight moment \((3)\), the overall impact of cell phone use on traffic flow could be substantial. Further research could estimate the extent of this impact using traffic microsimulation. By allowing participants to freely change lanes, the
car-following and lane-changing results from this research could be applied to a multilane freeway model. Moreover, the current research provides the necessary information for calibrating a traffic model: flow and speeds as basic input values; differences in the number of lane changes, total travel time, time in following/not following, and following distances for both single- and dual-task conditions.

Modeling a multilane freeway with various levels of congestion provides the ability to further investigate the macroscopic impact of distracted drivers for various traffic flows. This study demonstrates that driver simulator research can be designed to reflect various traffic flow conditions and generate dependent measures that could have application in traffic related research; thus, moving toward a bridge in the current gap between physical driving simulators and mathematical traffic microsimulator.

CONCLUSIONS

1. When conversing on a cell phone drivers made fewer lane changes in the medium and high density traffic scenarios.
2. Drivers on the cell phone spent more time following a lead vehicle; which increased travel time.
3. Following distance did not appreciably differ between single- and dual-task conditions.
4. In-vehicle cell phone use had no noticeable effect on turn signal usage.
REFERENCES


