



## Driver responses to differing urban work zone configurations

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### ABSTRACT

This study reports the results of a simulator-based assessment of driver response to two different urban highway work zone configurations. One configuration represented an existing design which was contrasted with a second configuration that presented a reduced taper length prototype work zone design. Twenty-one drivers navigated the two different work zones in two different conditions, one with and one without a lead vehicle; in this case a bus. Measures of driver speed, braking, travel path, and collision frequency were recorded. Drivers navigated significantly closer to the boundary of the work area in the reduced taper length design. This proximity effect was moderated by the significant interaction between lead vehicle and taper length and such interactive effects were also observed for driver speed at the end of the work zone and the number of collisions observed within the work zone itself. These results suggest that reduced taper length poses an increase in risk to both drivers and work zone personnel, primarily when driver anticipation is reduced by foreshortened viewing distances. Increase in such risk is to a degree offset by the reduction of overall exposure to the work zone that a foreshortened taper creates. The benefits and limitations to a simulation-based approach to the assessment and prediction of driver behavior in different work zone configurations are also discussed.

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### 1. Introduction

With the constantly increasing demands that society places on the communal road network, the associated construction and maintenance operations represent an undesired but necessary disruption to the smooth flow of transportation system operations. These required working areas present perennial challenges to operational safety on the roadway. Among the leading concerns created by work zone interruptions to smooth traffic flow is the fact that driver expectation of forthcoming roadway conditions is very often violated. Such violations occur because work zones are encountered relatively infrequently. They are thus difficult to predict in terms of their spatial location and also their temporal duration at any one location. As a result, the driver's first encounter with any particular work zone is liable to involve surprise and uncertainty together with the necessity to engage in avoidance maneuvering.

Driving through work zones then clearly elevates the risk of collision (Wang et al., 1996). Although work zones are relatively infrequent during everyday driving, they are highly over-represented in terms of their impact on road safety. Data for the year 2006 from the U.S. National Highway Traffic Safety Administration (NHTSA, 2008) recorded over 1000 fatal incidents in work

zones. In respect of elevated risk, Council et al. (2000) found that once inside the work zone the total crash rate was 21.5% higher than a comparable pre-work area. When crash frequencies are considered, Council et al. observed that the factors of work zone duration and length are those which most systematically contribute to this increase in risk. These are not unprecedented conclusions since previous researchers had earlier reported similar increasing collision trends. For example, Liste et al. (1978) recorded an increase of 119% in crash rate within evaluated work zones. In a dramatic example of this increase in relative risk, Roupail et al. (1988) reported an 88% higher crash rate (as compared to a pre-work zone period) at one long-term work area. Comparable short-term work areas saw a constant rate of 0.8 crashes per mile per day. These collective studies examined work zones at a wide variety of locations and on many different types of roadways. Their findings illustrate that, although some differences exist due to specific environmental factors, it is the spatial configuration and temporal persistence of work zones which play a dominant role in the number of accidents observed at any given site.

An analysis by Mohan and Zech (2005) identified five distinct types of work zone collision. Their examination of New York State Department of Transportation construction projects from 1999 to 2001 determined that the majority of incidents in the work zone could be classified as one of: (a) work space intrusion, (b) workers struck by vehicle inside work zone, (c) flag bearers struck by vehicles, (d) workers struck by vehicle entering/exiting the work space, and (e) construction equipment struck by vehicle inside work space. Thus workers operating inside the work zone are at

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particular risk since they lack the impact protection offered by a vehicle cab or any similar impact amelioration technologies. Essentially, they are unprotected pedestrians in particularly dangerous locations. Altogether, these 5 collision types accounted for almost 86% of fatal injuries and 70% of hospitalizations for lesser injuries experienced in the work zone area (Mohan and Zech, 2005; Pratt et al., 2001). In a more general assessment, Bryden and Andrew (2000) found work zone intrusion accidents accounted for 10% of all total traffic accidents and 8% of all serious injuries. Further studies have identified, for example, that collisions with flag-bearing personnel accounted for 50% of all total pedestrian accidents (Ore and Fosbroke, 1997). Based on these findings, any effort to improve the safety buffer between drivers and the vulnerable elements of the work zone is a critical step in increasing the safety of these transient roadway features. Obviously, from the overall reported crash data, any work zone improvements would serve to enhance the safety of the overall transportation system to a significant degree.

Reducing the vehicle velocity immediately preceding entry and at the actual onset of a work zone presents one of the most promising means of decreasing collision frequency and associated damage at these sites. However, this form of remediation is complicated by driver behavior patterns immediately prior to work zone entry. For example, a significant portion of drivers wait until the point of lane closure before they begin the process of merging (Benekohal et al., 1993). This often leads to situations where drivers can be unaware of the need to, or are unable to adequately slow or stop upon entering the work zone area (Sorock et al., 1996). As vehicle speed is a crucial factor in work zone-related collisions (Graham et al., 1977), some researchers have focused on developing strategies for reducing speed within and immediately prior to work zone entry. In one such effort, Rouphail and Tiwari (1985) found that although speed generally decreases through the work zone as the intensity of construction or maintenance activities themselves increases, simply controlling overall speed across the whole work zone also serves to reduce collision frequency (also see Rouphail et al., 1988).

Perhaps the largest contributor to potential safety improvements in work zones is forward signaling. The forewarning of the upcoming work zone allows drivers to make lane transitions earlier and in a more controlled manner. In a study examining driver expectancies in work zones, Pietrucha (1995) noted that drivers who traverse a long section of road within a work zone without encountering any signs, construction, or lane closure are unlikely to enter the directed lane until an obstacle is actually encountered. In situations where drivers perform such late lane changes, the associated crash risk increases. Accordingly, this has led some to conclude that appropriate and clear roadway markings are essential for safe work zone travel (Pietrucha, 1995). Properly configured pre-work zones are therefore a critical cue for drivers and serve to make information on the upcoming circumstances more accessible and useful (Godthelp and Riemersma, 1984; Pietrucha, 1995). Although there are effective measures to ensure drivers maintain safe speeds within work zones themselves (Hildebrand et al., 2005), making the transition into the work zone as safe and predictable for drivers is a practical key to work zone safety improvements.

One practical method of ensuring a safe and predictable transition out of a closing travel lane is through the use of tapering configurations. These transitional, channelized, lane closings require the driver to perform a mandatory lane change as the work zone approaches. The Manual of Uniform Traffic Control Devices (MUTCD; Federal Highway Administration, 2007) provides guidance for the lengths of these taper zones, albeit with the caveat that “longer tapers are not necessarily better than shorter tapers (particularly in urban areas with characteristics such as short block lengths or driveways) because extended tapers tend to encourage sluggish operation and to encourage drivers to delay lane changes unnecessarily (pp. 6C-5).” Understanding the practical effects of differing taper

lengths on approaches to work zones, especially in urban areas, may permit more accurate safety decisions to be made regarding their staging and configuration. However, the focus on the safety of work zones operates within a generally very cost-conscious environment. There are significant and constantly increasing costs associated with the setup and the removal of any work zone. Additionally, drivers often become frustrated by the delays and other associated penalties that work zones impose. This has led to interest in the possibility of using reduced entry length taper channeling into work zones, especially in urban environments. The use of shorter distances for channeling drivers out of the tapering travel lane would lead to clear and immediate financial benefits. However the safety risk associated with this strategy remains, at the present, largely undetermined.

As a result of these respective safety deliberations about diminished taper lengths as approaches to active work zones, the following, simulation-based, experimental evaluation was conducted. Specifically, the study was designed to examine the possibility of reducing vehicle speed and improving vehicle control prior to and within an urban work zone by manipulating the taper directly preceding that work zone. Existing research has dealt primarily with either highway or freeway work zone configurations. Thus, the present study not only examined the tradeoffs in spatial layout of the work zone entry area, but it also examined these configurations in the urban roadway environment. This procedure promised to render new insight into this relatively unexplored work zone setting. A simulator-based examination of driver performance was chosen since this experimental tactic provides many benefits in examining the safety impact whilst minimizing the potential for damage and injury under challenging driving conditions. Crash-likely scenarios may thus be created and tested with minimal risk for the driver. In the present case, close to ‘worst-case’ circumstances can be explored well before any final deliberations and decisions as to actual on-road implementations are made. Further, simulation-based testing means that highly precise data regarding driving behavior is obtained which would often be difficult, and occasionally impossible to record in the real world.

## 2. Experimental method

### 2.1. Experimental participants (drivers)

Twenty-one licensed drivers were recruited from a university population to serve as participants in the present study. The mean age of the 13 female and 8 male individuals was 21.14 years ( $SD=2.29$  years). All participants reported having normal color vision and normal or corrected-to-normal visual acuity. These drivers reported being in a normal state of health at the time of participation. Drivers in this study had held their full drivers license an average of 4.5 years ( $SD=2.58$  years). The majority drove every day (85.7%) and had an average annual mileage of over 10,000 miles per year (61.9%). The majority of participant’s normal driving environment included urban (85.7%) or other main roads (57.1%) such as the configuration examined in the present study. The total duration of the driving experience within the experiment was approximately 2 h. All participants were treated in accordance with the ethical principles of the American Psychological Association (APA), and were compensated for their time with \$20 USD.

### 2.2. Experimental apparatus

#### 2.2.1. The driving simulator

A fixed-base driving simulator (ISim, software version 4.0.85) was used as the testing platform in the present experiment. This simulator is based around the dashboard and major controls of a

Ford Crown Victoria sedan and operates via network of five inter-linked computers. The simulator itself monitors the driver's inputs and alters the vehicle trajectory within roadway environment in response to these control inputs. These changes are projected through three image channels (each channel's video output was 800 by 600 resolution) onto a screen placed approximately 1.0 m from the driver's eyepoint. This provided a horizontal field of view of approximately 120° for the driver. All communications within the simulator network were synchronized at 60 Hz, and logged by specially developed measurement software for subsequent off-line analysis.

### 2.2.2. Measurement software

In order to obtain accurate measurements of each driver's input and to control the presentation of stimuli within the driving environment, an interface to the simulator network was authored by the present research team using the LabVIEW programming language (National Instruments, software version 8.20). This program monitored the simulator network and provided a custom-developed interface for accurately controlling the introduction of specific simulation elements into the driving environment. This software package also logged all data for subsequent off-line analyses. Further, the software package allowed for initial screening analysis and quality assurance of the incoming data to be conducted through preliminary statistical and visual inspection. All variables to be measured were calculated or displayed as a function of time and synchronized with each other. After initial processing and inspection to ensure data were within expected response ranges, the software package tabulated the raw data that was exported for further analysis by a standard statistical package.

### 2.2.3. Driving environments and work zone configurations

Five different routes were constructed within the simulated urban highway-driving environment. This number was used in order to prevent performance transfer effects due to repeated exposure to any one single condition. Four routes contained the targeted work zones, while one route, which acted as a control, contained no work zone. Two factors were manipulated across the four work zone scenarios. The first factor was the presence or absence of a lead vehicle. The second factor was the length of the work zone, being either short or long. The two manipulations of the lead vehicle status created circumstances where the driver would follow a lead vehicle (a transit bus, chosen for its high degree of forward view interference) through the entire route. In the case of its absence, the driver would follow orange arrow signs through the entire route. In scenarios with the lead vehicle present, the vehicle followed a scripted travel speed and path. Participants were asked to follow this lead vehicle at a set headway (approximately 2 s). The bus's

path was set to change lanes as late as feasible into the taper without signaling. This presented conditions as close to the worst case as might be expected to occur in actual driving conditions.

Two work zone configurations were tested. These manipulations were based upon a change in taper length. They were each founded on the current Florida Department of Transportation (FDOT) design standard for the urban highway used in the present driving task (i.e., 2 travel lanes per direction, 72.4 km/h speed limit, 2.4 m shoulder). First, a 164.6 m taper length of standard channelizing devices (orange cones) was used. The second manipulation used a reduced taper length with cones closing the lane in a distance of 30.5 m. The cones were placed at a distance of 7.6 m apart. A plot of the layout and design of the work zones is given in Fig. 1. In all scenarios, additional roadway traffic was present in the on-coming travel lanes. Traffic was also present in the same travel lane that was occupied by the experimental driver and the lane immediately adjacent to them. This traffic served to increase driver workload within the work zone area and forced the driver to make a more succinct entry to the work zone. The make and model of roadway traffic was systematically varied across all trials, although their respective speed and travel paths were held constant across each scenario.

### 2.2.4. Driver performance assessment measures

Several performance measures were obtained from the driving simulator network. These included the driver's speed (upon entering, while within, and upon exiting the work zone), peak braking within the work zone (a measure chosen as an indication of the magnitude of sudden driver response), and the number of collisions observed. These measures were chosen to provide a comprehensive portrait of immediate driver control of the vehicle and their positive guidance (in terms of the driver's response to information provided by the roadway environment; see Russell, 1998). Overall, these measures capture a description of the nature and magnitude of driver adjustments and are a reflection of the overall safety of the work zone as encountered.

An additional measure was calculated in order to characterize the path drivers took through the work zone. This measure represented the area (expressed in square meters [ $m^2$ ]) between the center of the driver's own vehicle and the boundary of the work zone. This latter threshold was defined by the work zone channeling devices (i.e., the orange cones). Representative areas were calculated for the first three cones of the work zone. This method of path determination was chosen over other possible methods such as the vehicle's standard deviation of lane position within the simulated environment. The latter is an informative measure; however it can be an equivocal one in this case since there are many equally appropriate paths of travel through the work zone. This "area computation" method thus provides a measure of travel path that does

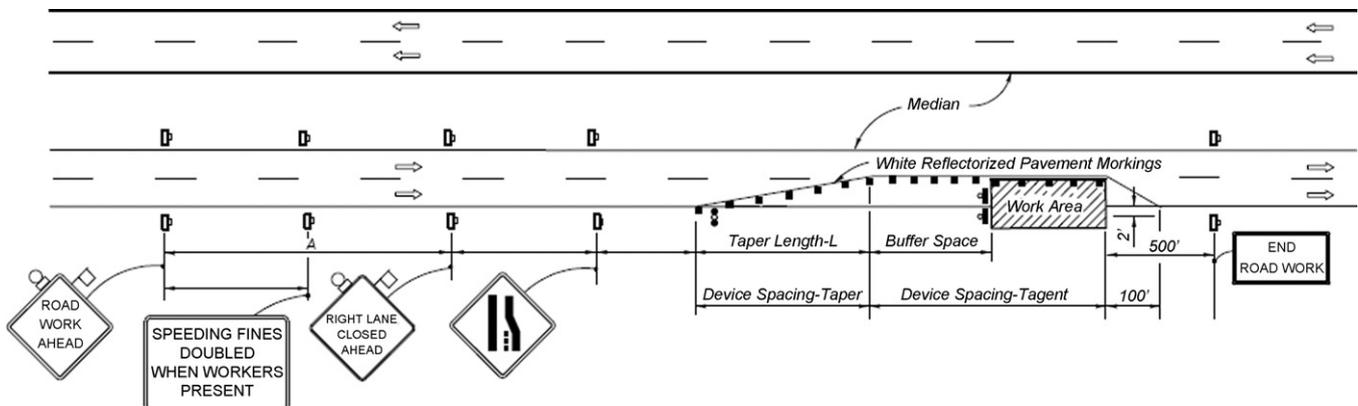


Fig. 1. Florida Department of Transportation (FDOT) design standard 613, multi-lane work zone design.

not rely on an ideal travel path or lane center to describe deviations towards the work zone area. This present performance reflection is thus here derived and is proposed by us as a more valid measure of the likelihood of vehicle intrusion into the operational region of the work zone. Area measurements, calculated at each of the first three cones, were then compared across conditions. In addition to these objective measures, a brief history of their driving experience was obtained from each driver.

### 2.2.5. Experimental procedure

Following the completion of the informed consent materials, the participants were given information as to the layout and operation of the driving simulator. This information included the location of all controls (steering, throttle, brake, gear selection, etc.) and adjustments (seat, steering wheel, etc.). Participants then completed a brief familiarization route consisting of approximately 3.2 km (2 mi) of driving while following orange arrow signs. This was followed by approximately 3.2 km (2 mi) of driving while following a lead vehicle. At the conclusion of this familiarization scenario (and every subsequent trial), drivers were allowed a brief break in which they could stand and stretch as needed. This break also served to allow the experimenter to reset the simulation and helped to lessen any ocular and gastrointestinal discomfort that might be felt due to the driving simulator (see Kennedy et al., 1993).

Each participant then completed a total of twenty drives in the simulated environment. Four scenarios were based on the two independent variables of lead vehicle (two levels: present and absent) and work zone configuration (two levels: the existing, standard, design and the reduced taper length design) whilst the remaining scenario contained no such circumstances. Each of these individual scenarios was experienced four times by each participant. Trials were presented in a counterbalanced order. Participants drove through each scenario, following either the lead vehicle or the orange arrow signs (used for driver navigation in scenarios without a lead vehicle), until they reached a vehicle on the roadway shoulder which was their signal to stop and park their vehicle.

## 3. Results

All data was screened for normalcy and violations of test assumptions prior to analysis. The one exception to these basic assumptions for collision frequency is highlighted below. All analyses were conducted using SPSS for Windows, version 14, using a present significance level set at  $\alpha = .05$ . Only trials with a work zone configuration present were included in the present analysis.

### 3.1. Speed across work zones

Vehicle speed was measured at multiple points while the driver traversed through the work zone location. The initial measurement was obtained 60 milliseconds (ms) prior to work zone entry, while exit speed was measured at 60 ms following the driver's exit from the work zone. This allowed for a comparison of pre- and post-work zone speed. In addition, drivers' mean speed within the work zone was calculated and used in the analysis.

The main effect for lead vehicle on pre-work zone speed was significant,  $F(1, 19) = 71.945, p < .001$ . When collapsed across taper lengths, participants drove significantly faster when the lead vehicle was absent ( $M = 78.5$  km/h,  $SE = 1.0$  km/h) compared to when the lead vehicle was present ( $M = 68.0$  km/h,  $SE = 0.5$  km/h). Although this main effect proved reliable, the interaction between lead vehicle status and taper length for speed upon entering the work zone was not significant. Also, the main effect of taper length on pre-work zone speed was not significant ( $p > .05$ ). When drivers were within the work zone a similar pattern in speed response

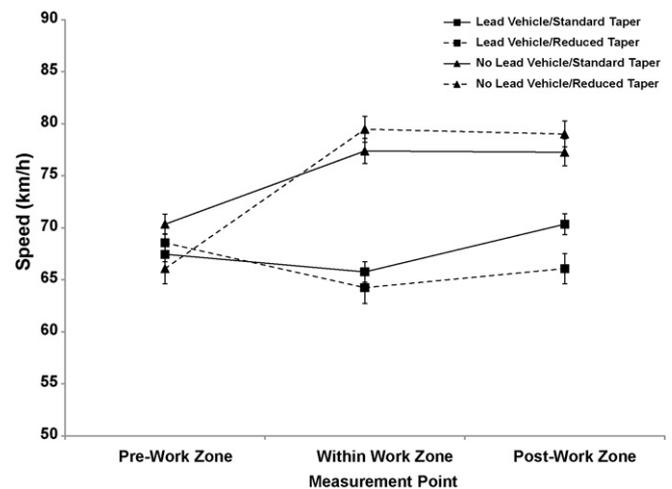


Fig. 2. Interactive effect of taper length and the presence or absence of a lead vehicle on driver speed through the various phases of the work zone.

was evident. The main effect for lead vehicle remained significant,  $F(1, 19) = 77.879, p < .001$ . That is, when collapsed across taper lengths, participants drove significantly faster through the work zone when the lead vehicle was absent ( $M = 78.4$  km/h,  $SE = 1.0$  km/h) compared to conditions where the lead vehicle was present ( $M = 65.0$  km/h,  $SE = 1.0$  km/h). The main effect for taper length was non-significant,  $F(1, 19) = 0.046, p > .05$ . At the termination of the work zone, the interaction for lead vehicle by taper length for the measure of post-work zone speed was significant,  $F(1, 19) = 12.326, p = .003$ . This result showed that without the presence of a lead vehicle, taper length had no effect on post work zone speed (i.e., standard taper configuration  $M = 77.3$  km/h,  $SE = 1.3$ ; reduced taper configuration  $M = 79.0$  km/h,  $SE = 1.2$  in.,  $p = .34$ ). However, in the presence of a lead vehicle, the reduced taper suppressed vehicle speed compared to the standard taper condition (i.e., standard taper configuration  $M = 70.3$  km/h,  $SE = 1.0$ ; reduced taper configuration  $M = 66.1$  km/h,  $SE = 1.5, p = .025$ ). This result for a speed change only at the third cone may be due to the timing involved. Thus for a vehicle traveling at 72.4 km/h, it would take only approximately 1 s to traverse the distance between all three cones. It is suspected that this latency represents the time that drivers took on average to respond. Considering the overall pattern of speed findings presented in Fig. 2, it is clear the presence of a lead vehicle has an important influence on the speed profile as drivers progressed through the work zone area. However, it is critical also to note that this effect is modified by the difference in taper length as the driver exits the work zone location.

### 3.2. Peak braking

In order to assess the portraiture of driver braking, an interval consisting of the period 500 ms prior to the driver entering the work zone was selected. This was compared to an interval of 500 ms following the driver exiting the work zone. Within each interval, the peak brake actuation (in terms of the percent of pedal actuation) was recorded and analyzed. There was a significant main effect for the lead vehicle presence on this measure of peak braking,  $F(1, 19) = 36.106, p < .001$  (lead vehicle was present  $M = 16.9\%$  actuation,  $SE = 2.6\%$  versus lead vehicle absent  $M = 1.1\%$  percent,  $SE = 0.6\%$ ). The comparable main effect for taper length on peak braking was non-significant ( $p > .05$ ). As the interaction between lead vehicle and taper length for peak braking was not significant follow-up analyses were not conducted. Means and standard errors for peak braking are given in Table 1. It is evident that driver braking behavior differences are triggered by the presence of the lead

**Table 1**  
Means and standard error of peak braking observed within the work zone.

Taper length	Peak braking (in percent actuation)	
	Lead vehicle present	Lead vehicle absent
Standard	16.990 (3.529)	1.044 (0.740)
Reduced	16.837 (3.327)	1.227 (0.586)

vehicle and not the work zone taper length in the present circumstances.

### 3.3. Work zone travel path

The overall results for the measure of vehicle to work zone threshold at the three cone locations is illustrated in Fig. 3. The inter-cone distance in the present set up was 7.6 m. With respect to the measure of work zone travel path, results showed that the interaction between lead vehicle and taper length for total area between the driver's vehicle and the first cone was significant,  $F(1, 17) = 16.238, p = .001$ . Post hoc analysis, using Tukey's HSD procedure, was generated in order to identify the specific conditions contributing to the interaction. The vehicle-to-cone area was significantly smaller when a lead vehicle was present versus absent for both the standard (lead vehicle present  $M = 0.84 \text{ m}^2, SE = 0.04 \text{ m}^2$  versus lead vehicle absent  $M = 1.03 \text{ m}^2, SE = 0.01 \text{ m}^2$ ) and reduced taper (lead vehicle present  $M = 0.44 \text{ m}^2, SE = 0.04 \text{ m}^2$  versus lead vehicle absent  $M = 0.81 \text{ m}^2, SE = 0.02 \text{ m}^2$ ) work zones, respectively. Notably, the largest difference occurred for conditions where the lead vehicle was absent in a standard work zone ( $M = 1.03 \text{ m}^2, SE = 0.01 \text{ m}^2$ ) and conditions where the lead vehicle was present in the reduced work zone configuration ( $M = 0.44 \text{ m}^2, SE = 0.04 \text{ m}^2$ ). With respect to the present measure, the lower the value for the area recorded, the less safe that driver tends to be at that point of the work zone. With respect to this area measure of proximity to the boundary of the entry to the work zone as represented by the first cone, the main effects for both lead vehicle and taper length were also significant,  $F(1, 19) = 72.890, p < .001$  and  $F(1, 19) = 135.435, p < .001$ , respectively. When collapsed across taper length, participants had a much smaller vehicle-to-cone area when the lead vehicle was present ( $M = 0.64 \text{ m}^2, SE = 0.03 \text{ m}^2$ ) compared to when the lead vehicle was absent ( $M = 0.92 \text{ m}^2, SE = 0.01 \text{ m}^2$ ). With respect to vehicle-to-cone clearance, a much smaller distance was observed for the reduced taper work zone ( $M = 0.62 \text{ m}^2,$

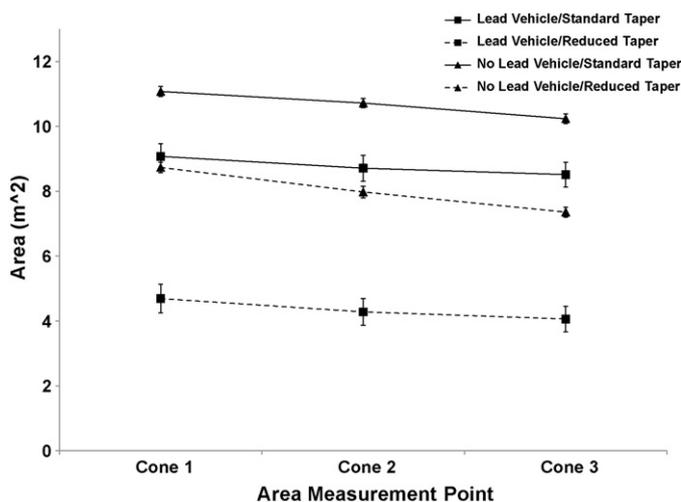
$SE = 0.02 \text{ m}^2$ ) compared to the standard work zone configuration ( $M = 0.94 \text{ m}^2, SE = 0.02 \text{ m}^2$ ).

With respect to the second cone in the sequence of three recorded, the total vehicle-to-cone area showed a similar pattern to those observations recorded for the first cone. That is, the interaction for lead vehicle by taper length for total area at the second cone once again proved significant,  $F(1, 17) = 8.619, p = .009$ . Post hoc analyses using Tukey's HSD procedure again showed that the comparison between lead vehicle present/standard taper and lead vehicle absent/reduced taper was not significantly different. However, all other factor levels significantly differed from each other. The vehicle-to-cone area was significantly smaller when a lead vehicle was present versus absent for both the standard ( $M = 0.81 \text{ m}^2, SE = 0.04 \text{ m}^2$  versus  $M = 1.0 \text{ m}^2, SE = 0.01 \text{ m}^2$ ) and in the reduced ( $M = 0.40 \text{ m}^2, SE = 0.04 \text{ m}^2$ ) versus standard ( $M = 0.74 \text{ m}^2, SE = 0.02 \text{ m}^2$ ) work zones, respectively. The main effects for both lead vehicle and taper length were also significant for the vehicle-to-cone area at the second cone,  $F(1, 19) = 95.073, p < .001$  and  $F(1, 19) = 162.259, p < .001$ , respectively. Similar to the results recorded at the first cone, when collapsed across taper length, participants had a much smaller vehicle-to-cone area when the lead vehicle was present ( $M = 0.60 \text{ m}^2, SE = 0.03 \text{ m}^2$ ) compared to when the lead vehicle was absent ( $M = 0.87 \text{ m}^2, SE = 0.01 \text{ m}^2$ ). Also, drivers had a much smaller vehicle-to-cone clearance for the reduced taper work zone ( $M = 0.57 \text{ m}^2, SE = 0.02 \text{ m}^2$ ) compared to the standard work zone configuration ( $M = 0.90 \text{ m}^2, SE = 0.02 \text{ m}^2$ ). These consistent findings indicate that drivers did not change their behavior drastically from the work zone entry area to the next part of the work zone, that is, from the site of cone one to the site of cone two.

The results recorded at the third and final cone very much replicated those at the two prior sites. Thus, the interaction between lead vehicle and taper length for total area at the third cone was also significant,  $F(1, 17) = 9.692, p = .006$ . Post hoc analyses, again using Tukey's HSD procedure, showed the comparison between lead vehicle present/standard taper and lead vehicle absent/reduced taper was not significant. However, again in a consistent manner with the two previous sites, all other factor levels proved significantly different from each other. The vehicle-to-cone area was significantly smaller when a lead vehicle was present versus absent for both the standard ( $M = 0.79 \text{ m}^2, SE = 0.04 \text{ m}^2$  versus  $M = 0.95 \text{ m}^2, SE = 0.0 \text{ m}^2$ ) and reduced ( $M = 0.38 \text{ m}^2, SE = 0.04 \text{ m}^2$  versus  $M = 0.68 \text{ m}^2, SE = 0.01 \text{ m}^2$ ) work zones, respectively. Similarly, when collapsed across taper length, participants had a much smaller vehicle-to-cone area when the lead vehicle was present ( $M = 0.58 \text{ m}^2, SE = 0.03 \text{ m}^2$ ) compared to when the lead vehicle was absent ( $M = 0.82 \text{ m}^2, SE = 0.01 \text{ m}^2$ ). Also, drivers showed a much smaller vehicle-to-cone clearance in the reduced taper work zone ( $M = 0.53 \text{ m}^2, SE = 0.02 \text{ m}^2$ ) compared to the standard work zone configuration ( $M = 0.87 \text{ m}^2, SE = 0.02 \text{ m}^2$ ). These findings for performance at the site of the third cone again emphasized the consistency in driver responses to the manipulated conditions. To reiterate, the overall findings for this measure are shown in Fig. 3.

### 3.4. Collision frequency

Collision frequency was analyzed for the four experimental conditions. A total of 8 collisions were observed across all recorded trials: 7 occurred in the lead vehicle present condition in the reduced taper work zone. One collision occurred in the lead vehicle present condition in the standard taper work zone. No collisions occurred, under either condition, when the lead vehicle was absent. Collisions in the two lead vehicle present conditions were compared using Fisher's exact test, which indicated no statistical difference in collisions based on taper length ( $p = .19$ ). These results may be seen as suggestive of an overall effect for the presence of



**Fig. 3.** Interactive effect of taper length and lead vehicle on the proximity to the three cone locations in the work zone as measured by the area value at those respective points.

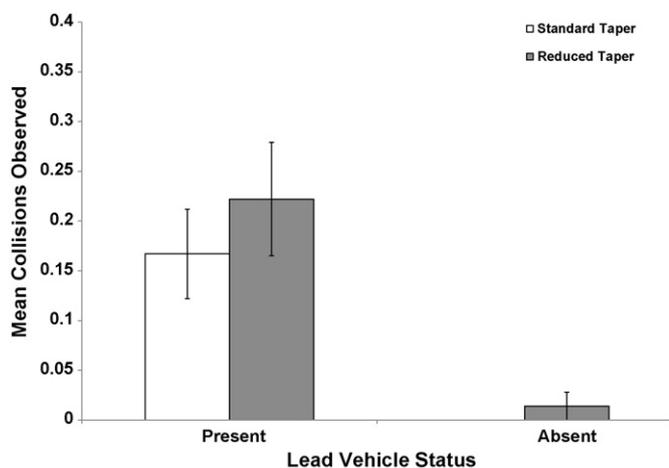


Fig. 4. Collision events parsed by taper length and the presence or absence of a lead vehicle. Such collisions only occurred with work zone elements.

a visually occluding lead vehicle on the collisions observed in the present experiment. The mean number of collisions observed in each condition is presented in Fig. 4.

#### 4. Discussion

The purpose of the present experiment was to evaluate the effect on driver performance of reducing the standard taper length of an urban highway work zone. Although reducing the overall physical length of work zones reduces cost in terms of setup and breakdown times, as well as increasing traffic throughput, the risk of a potential increase in collision likelihood must be considered as an offsetting factor in any comparative design selection decision. In addition to considering the work zone taper length here, we also evaluated the presence of a lead vehicle. In large part this was a purposive decision designed to understand driver response in close to ‘worst case’ circumstances when a particularly large vehicle acted to occlude the driver’s line of sight. In keeping with the worst case condition, we evaluated performance in an urban environment in which traffic also appeared in close proximity to the driver’s own vehicle. Visually compromising conditions present particularly challenging circumstances with respect to the safe entry into and travel through an urban work zone. As well as these variables inherent to the scenario, we created the condition in which the lead vehicle made a sudden and unexpected lane change maneuver upon entering the work zone. This maneuver proved similar to circumstances where the lead vehicle’s driver was disturbed by some form of distraction on approaching the work zone (Hancock et al., 2008). These collective variables clearly presented significant challenges to the following driver. Thus, results from the present investigation are representative of the more extreme circumstances that might be found in real-world conditions. Consequently, the present information provides decision-makers with close to worst possible case circumstances.

The analysis of the effects of taper length on the overall portrait of driver performance imply that the present reduction in taper length of 134.1 m (i.e., from 164.6 m to 30.5 m) did not itself have an especially deleterious effect on immediate vehicle control. For example, there were no significant effects for taper length on pre-work zone speed. The only effect on speed was an interactive one at the latter end of the work zone in which the occluding vehicle played a critical role. Again, considering the effects for taper length alone, there were no significant influences on braking behavior. Collectively, these results suggested relatively little effect of differing taper length on the drivers’ longitudinal control of their

vehicle. However, there were effects for taper length on the path of travel itself as represented by the area proximity measure. These lateral control influences did not interact with the site of the respective cones and thus did not vary as a function of location within the work zone. Drivers behaved differently as a function of taper design. The shorter taper design influenced the drivers to navigate closer to the work zone threshold through its whole length. From these main effects it would appear that taper length affects the lateral positioning of the vehicle but has relatively little influence on on-going longitudinal control. However, before we settle for such a conclusion, it is critical to consider the strong interactive effects.

When we factor in the visually obstructive lead vehicle, as it is indeed a circumstance that is often present in crowded urban driving, then a more elaborated outcome pattern is observed. Here we find numerous interactions such that the combination of a shortened work zone taper combined with an occluding influence does lead to a modified pattern of driver response. Now, the combined effects of taper length and presence of a leading vehicle produce systematic changes in speed as the driver progresses through the work zone. This is especially true of the transition into the work zone itself that, as noted earlier, has a strong influence on overall safety. Further, we find that although differences in braking patterns are completely mediated by the behavior and presence of the lead vehicle, the proximity to the threshold of the work zone is again contingent upon the interactive effects. Overall, we can assert that changes in the pattern of longitudinal control appear to be directly related to the leading vehicle. Although this is not a startling finding, it is an important one for those who have to decide on the possible design and implementation of foreshortened urban work zone tapers. As is clear from these results, the lateral safety margin is at its lowest in the reduced taper condition with the lead vehicle present. In itself this does not necessarily equate to a higher frequency of collision but the area measure itself is suggestive.

Fortunately, in the present experiment we can examine the frequency of collisions directly. Here we can see that the standard taper length, if not obscured by any occluding influence led to no collision events whatsoever. However, this changes with the presence of a lead vehicle. There are a small number of collisions due solely to the reduced length taper and the respective increase when a lead vehicle is present in these latter conditions is disproportionately larger. As the strict measure of work zone effects, object collision frequency has limited explanatory power. However, as has been described, this study also used the vehicle-to-cone area measure to address ‘close-calls’ or heightened risk that may result from poor driver performance. The pattern for both the collision frequency and the area proximity measure tended to be very similar. Indeed, the order of the conditions, in terms of their safety implications is coincident for the two separate measures. That is, a short taper with a lead vehicle present is the most dangerous condition and longer taper with no lead vehicle the safest for both measures of collision frequency and area proximity.

In evaluating these collective findings for their relevance to work zone design, we must consider other important factors. First, given the fixed space within the work zone area, an increase in subtended entry angle to the work zone is a natural consequence of a shortened work zone taper. Thus, the driver has less time to perceive and respond to the appearance of the work zone (Morgan and Hancock, 2009) and it is known that proportional mistakes in time-to-contact estimates increase with such reduced time for response (Hancock and Manser, 1997). These increasing spatial and temporal demands on response increase especially when no prior warning signage is presented. One can thus envision how risk would then be additionally increased in low-visibility conditions due to fog, rain, snow, and similar environmental disturbances. The

increasing work zone taper angle produces the need for quicker and more pronounced driver corrective actions. This produces a situation which may increase the already present risk faced within a work zone, and the level of risk could possibly be further magnified by environmental disturbances. The current study also evaluated driver behavior when evasive maneuvers into a parallel lane were not always a safe alternative. In general, this manipulation produced a greater number of crashes mostly occurring with the principal work zone channelizing devices or from being rear-ended because of greater peak braking observed when the lead vehicle was present compared to conditions where the lead vehicle was absent. Each of these conclusions has to be tempered by our knowledge that the present results derive from simulation in which the penalties for such mistakes are negligible. The central issues as to exactly how simulation findings translate to real-world experience is thus the concern of our final concluding section of the present work.

#### 4.1. The applicability of simulation evaluations

Simulation, whether human-in-the-loop simulation that examines driver performance or traffic modeling designed to examine congestion and traffic flow, provides a valuable tool for the transportation safety researcher. Ideally, information concerning driver performance in simulated environments provides high quality data in order to more accurately model and subsequently design the real world. The utility of such design changes can then be confirmed through subsequent naturalistic driving studies. This was the applied purpose of the present experiment which was derived from real-world questions posed by State Traffic Engineers. The information that can be obtained from simulation is often the only such information possible about highly risky, real-world conditions. Obtaining such information in the real-world often exposes drivers to unacceptable levels of risk and exposes authorities to unacceptable levels of legal culpability. In these circumstances, simulation provides a convenient and informative route to examine specific issues of roadway environment safety with no fundamental risk of injury or death.

Unfortunately, as with all methodologies, simulation comes with its own inherent limitations. The omnipresent question is how accurate a simulated experience is compared with the external reality outside the virtual experience. Simulators need to be validated, but very rarely does any agency keen to make use of simulation facilities pay for such validation procedures. From the “physical” reactions of the vehicle to the interaction with other elements in the roadway such as other cars and traffic signals, does what is presented to the driver form a convincing simulacrum? Developers of modern driving simulators tend to focus primarily on obtaining the ultimate in visual and (occasionally) tactile-kinesthetic and other forms of sensory fidelity. This search is a goal of all simulation-based research (see Hancock, 2009; Hancock and Sheridan, *in press*). From a pragmatic perspective, it can be argued that the fidelity of the underlying psychomotor tasks (functional fidelity) is the most important concern. Thus, is the relationship between the operations of the simulated vehicle consistent to the operation of the real vehicle? Validation of such a relationship would allow for a high degree of generalizability from such simulation studies. Providing the limits of specific simulators are well understood, adequate functional fidelity is preferable over any increases in the physical/perceptual fidelity (Hancock, 2009). The ever-increasing level of fidelity in simulation may be a process of chasing a rather destructive end. This is because, as some researchers have argued, higher levels of fidelity may be detrimental to experimental control (through data collection limitations, increased prevalence of simulator sickness, and introducing limits to data collection; Lee, 2004). Although the use of driving simulators must be considered

in respect of generalizability and fidelity issues, the information gained from their use has and continues to provide crucial knowledge of driver performance in a variety of settings (Hancock and Sheridan, *in press*).

As a relatively unexplored area of traffic safety, the issue of work zone design and especially the question of taper configuration in urban terrain is one that ought to benefit from further investigation and simulation would currently appear to be the best avenue through which to approach such issues. These issues concern the influence of moderating factors such as day/night driving, weather variations, work zone length, traffic density, driver personality, and experience. Each needs to be understood in the context of modern work zone operations. These considerations also need to be framed against the present-day sources of driver distraction (see Regan et al., 2008). Modern thieves of attention continue to proliferate in the driving world and devices such as cell phones, navigational aids, and the like must be included in future simulation-based evaluations of driver behavior in all contexts, including work zone assessment. Therefore, although we believe the results of the present experiment can be helpful to designers of current and future transportation systems, we are well aware of their potential shortcomings and limitations. Like all safety scientists, we are engaged in a continuing battle to improve our methods and approaches to serve the goals of increasing safety. Given the costs associated with injuries and fatalities associated with all forms of transportation failures, this remains a strong imperative for social investment.

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