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IMPROVED METHODS FOR DELINEATING DIVERGES IN WORK ZONES

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16. Abstract:

This report presents results from an investigation regarding the impacts of various delineation methods on driver performance in properly identifying the condition and location of work zone diverges. The motivation for this research program stems from the needs to (1) understand the fundamental principles behind driver perception of traffic control devices in a work zone; (2) understand how the design and configuration of work zone traffic control devices interact with these principles to impact human performance; and (3) develop cost-effective screening methods to test new designs and configurations. To address these needs, a testing method was developed in which computer-rendered still images (near photo-realistic) of various work zone environments were briefly shown to participants who were asked to identify (1) the location of a diverge within a work zone and (2) its condition (i.e., open or closed) when given a very limited response time.

To examine these issues, three separate but related experiments were conducted. In each, the responses from participants were collected and analyzed in terms of percent correct, several error types, and the observed latency (time delay) in making the ramp identification decision. In almost all circumstances delineation devices that maintained continuity and linearity throughout the desired path resulted in better human performance. The experiments also showed that when a construction project requires the full closure of a ramp then driver understanding of delineation becomes increasing challenging. Finally, in several instances, scenarios without delineation equipment showed greater errors. This observation indicates that the presence of equipment may provide additional cues signaling active work zones to drivers.

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Final Report

IMPROVED METHODS FOR DELINEATING DIVERGES IN WORK ZONES

By

Michael Hunter, Ph.D. (PI)

Michael O. Rodgers, Ph.D. (Co-PI)

Gregory Corso, Ph.D.

Yanzhi Ann Xu, Ph.D.

Aaron Greenwood

School of Civil and Environmental Engineering and
Georgia Institute of Technology

Contract with

Georgia Department of Transportation

In cooperation with

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Federal Highway Administration

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Executive Summary

This report presents results from an investigation regarding the impacts of various delineation methods on driver performance in properly identifying the condition and location of work zone diverges. The motivation for this research program stems from the needs to (1) understand the fundamental principles behind driver perception of traffic control devices in a work zone; (2) understand how the design and configuration of work zone traffic control devices interact with these principles to impact human performance; and (3) develop cost-effective screening methods to test new designs and configurations. To address these needs, a testing method was developed in which computer-rendered still images (near photo-realistic) of various work zone environments were briefly shown to participants who were asked to identify (1) the diverge location and (2) its condition (i.e., open or closed) when given a very limited response time. The use of computer-rendered images allowed for significantly greater control of the various environmental factors (e.g., lighting, visual background, etc.) and work zone configurations than could be achieved from "real world" images. Using still images also allowed for rapid data collection from a large sample of participants across multiple replications and conditions.

To examine these issues, three separate but related experiments were conducted. In each, the responses from participants were collected and analyzed in terms of percent correct, several error types, and the observed latency (time delay) in making the ramp identification decision. Combined, these factors paint a fairly comprehensive picture of driver perception of work zone diverges.

Experiment 1 was designed to compare uncluttered images of existing channelizing devices. These devices included standard highway drums spaced either 10 ft. or 40 ft. apart; drums spaced 40 ft. apart with a ± 2 ft. placement error, and portable concrete barriers (PCBs). These devices were tested with several road geometries under both open and closed ramp conditions. A "No Work" configuration (i.e. a ramp scene with no work zone present) was also included. Experiment 2 included additional images containing a proposed linear channelizing device (LCD) to test the perceptual hypotheses the research team developed based on the Experiment 1 results and the fundamental Gestalt principles regarding human perception. In Experiment 3, the researchers increased the image complexity by including roadside vegetation and construction vehicles to allow testing of more realistic images.

Although the three experiments approached the issue of delineation in work zone diverges with varying combinations of devices and configurations, the results regarding each channelizing device were relatively consistent across the experiments. In almost all circumstances under open ramp conditions, the use of PCB, LCD, and LCD missing 10% of pylons resulted in better human performance than the drum alternatives. The drums at 10 ft. and 40 ft. tended to perform similarly, although at a level below that of the PCB and LCD alternatives. This similarity implies that there is likely minimal advantage to any of the drum spacings considered. The drum

alternatives with ± 2 ft. misplacements almost always resulted in significantly lower percent correct than the other channelizing devices. Similar results were seen under ramp closed conditions with the exception that under longer time-to-exit distances LCD and well-aligned drum options tended to show similar identification (open/closed) error rates. This result implies that when a construction project requires the full closure of a ramp then PCB may be the best option. Differences between treatments tended to become more significant as distance to the diverge increased.

The impact of roadside vegetation and equipment was not discernible in most situations. However, at a significant distance from the diverge and when the ramp was closed, scenarios without equipment present showed greater errors. This observation indicates that the presence of equipment may provide additional cues signaling active work zones to drivers. Drivers may find that empty work zones without active construction are more difficult to interpret than work zones with active work.

These results provide several important implications in real-world work zone design and maintenance. First, more robust driver guidance may be needed when the ramp is closed, as drivers appear to have a more difficult time processing a closed ramp scene versus an open one. Second, linearity of the channelizing device seems to have a significant impact on driver perception of work zone diverges. In real-world applications, it may be of critical importance to maintain a linear alignment of drums. Third, given the improved human performance and the reduced costs associated with the proposed LCD, it may be a promising alternative relative to PCB.

Glossary

ANOVA: Analysis of Variance, a statistical procedure for determining the relative contribution of different factors to the variability of an outcome.

channelizing device: A device "to warn road users of conditions created by work activities in or near the roadway and to guide road users. Channelizing devices include cones, tubular markers, vertical panels, drums, barricades, and longitudinal channelizing devices. Channelizing devices provide for smooth and gradual vehicular traffic flow from one lane to another, onto a bypass or detour, or into a narrower traveled way. They are also used to channelize vehicular traffic away from the work space, pavement drop-offs, pedestrian or shared-use paths, or opposing directions of vehicular traffic." (FHWA 2009)

diverge: A separation of a single traveled way into two or more traveled ways, usually as an exit from a freeway.

drum: A cylindrical channelizing device with orange and white surface markings constructed of lightweight, deformable materials in accordance with MUTCD Section 6F.67.

geometry: The specific vertical and horizontal curvature of a roadway.

Linear Channelizing Device (LCD): A channelizing device consisting of a 60 cm wide and 8 cm high trapezoidal base with a white top and orange sloping sides, and regularly spaced vertical tubular markers. This device was developed for this research project.

MUTCD: The Manual on Uniform Traffic Control Devices, issued by the Federal Highway Administration, which governs the size, shape, color, illumination and retro-reflectivity, legend, border, and placement of traffic control devices used in the United States.

portable concrete barrier (PCB): A temporary traffic barrier constructed of concrete in a shape compliant with agency specifications (e.g., California Department of Transportation K-Rail) that, when placed end-to-end with other portable concrete barriers, forms a continuous wall for separation of traffic.

temporary traffic control (TTC) zone: "an area of a highway where road user conditions are changed because of a work zone, an incident zone, or a planned special event through the use of TTC devices, uniformed law enforcement officers, or other authorized personnel." (FHWA 2009)

time-to-exit: the time for a vehicle traveling at 60 miles per hour to reach the start of the taper leading to the diverge point.

traffic control device: "all signs, signals, markings, and other devices used to regulate, warn, or guide traffic, placed on, over, or adjacent to a street, highway, pedestrian facility, bikeway, or private road open to public travel by authority of a public agency or official having jurisdiction, or, in the case of a private road, by authority of the private owner or private official having jurisdiction." (FHWA 2009)

work zone: "an area of a highway with construction, maintenance, or utility work activities. A work zone is typically marked by signs, channelizing devices, barriers, pavement markings, and/or work vehicles. It extends from the first warning sign or high-intensity rotating, flashing, oscillating, or strobe lights on a vehicle to the END ROAD WORK sign or the last TTC device." (FHWA 2009)

Abbreviations

AADT	annual average daily traffic
ANOVA	Analysis of Variance
Caltrans	California Department of Transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
ft.	US customary feet
GDOT	Georgia Department of Transportation
JPEG	Joint Picture Expert Group file format
km/h	kilometers per hour
LCB	longitudinal channelizing barricade
LCD	Linear Channelizing Device
m	meters
mph	miles per hour
MDOT	Michigan Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
NCDOT	North Carolina Department of Transportation
NYSDOT	New York State Department of Transportation
NHTSA	National Highway Traffic Safety Administration
PCB	portable concrete barrier
QA/QC	quality assurance/quality control
TTC	temporary traffic control

1 Introduction

1.1 Background and Purpose

The safe use of highways and other transportation infrastructure remains the highest priority for both the U.S. Federal Highway Administration (FHWA) and State Departments of Transportation (DOTs), including Georgia DOT. A key factor in establishing a safe environment is the development of simple, consistent, and readily understandable ways for individuals to interact with the infrastructure. However, when roadways are undergoing maintenance or construction, additional guidance may be required to convey the necessary information for drivers and other roadway users to navigate through the "work zone" safely and efficiently.

1.1.1 Work Zone Safety

Given this need for additional guidance, work zone safety is an area of concern at both the national and state level. Not surprisingly, the presence of a work zone significantly increases the probability of a crash in a particular location. In a survey of work zone crash studies, Ullman, Finley, and Bryden (2008) found that the number of collisions increased by 20% to 30% within a work zone. There have been more than 600 work zone fatalities recorded in Georgia over the last decade (National Work Zone Safety Information Clearinghouse 2009). While driver impairment and/or excessive speed are major causal factors, driver confusion is also known to be either a cause or a confounding factor in many fatal crashes (National Work Zone Safety Information Clearinghouse 2009).

These increased risks are not unexpected. Even for drivers familiar with a roadway, the presence of a work zone may result in unfamiliar traffic patterns and lane configurations. These new paths may be delineated by sparse and sometimes inconsistent configurations of temporary traffic control devices. These temporary traffic control devices may be used within the work zone to indicate various road settings, including active work areas, travel lanes, lane shifts, and lane closures, as well as other conditions.

1.1.2 Diverges

Of particular concern to the safe traversal of a work zone is how to ensure that drivers of vehicles leaving an active travel lane at a roadway diverge (e.g., at a freeway exit) can (1) identify the presence of this diverge and (2) navigate the correct pathway without intruding into the active work area.

The safety implications of incorrectly identifying the proper pathway can be significant. In a study of work zone crashes in New York State between 1993 and 1998, Bryden, Fortuniewicz,

and Andrew (2000) estimated that 3.4% of work zone crashes resulted from a vehicle intruding into the active work zone while trying to exit the roadway.

The primary objective for this research project was to develop and evaluate improved methods and devices for work zone delineation, with a specific focus on diverges. Diverges within work zones can be particularly difficult for drivers, as their desired path is separated from the main roadway using channelizing devices. Thus, improvements in delineation that prove effective for diverges will likely have broader applicability throughout the work zone.

1.1.3 Delineation Systems

In the broadest sense, delineation systems are collections of control devices (e.g., roadway markers) that provide the driver with information regarding the path, demands, and special characteristics of the road. When applied to work zones, delineation systems have the primary responsibility for (1) informing drivers and construction workers of the allowed pathway for traffic through the work zone and (2) differentiating these pathways from other areas (i.e., active work, storage, etc.).

These delineation systems comprise a number of components and parameters that may be varied singly or in combination. For example, the type of delineator (e.g., post vs. barrel) and its physical characteristics (e.g., size, shape, color, construction, and presence of reflective material and illumination) may vary either within a work zone or between work zones. Likewise, how these components are used may vary, including the number, spacing, and selection of system elements, as well as their placement height and lateral positioning. Given the range of components and parameters available, many different delineation system layouts are possible for a given work zone.

This broad array of potential configurations may, to some extent, compromise the ability of these delineation systems to define and identify specific paths (e.g., exit ramps vs. through lanes). This may be thought of as a “signal-to-noise” problem in which the presence of a large number of delineation elements makes identification of path-specific information more difficult. Thus, a reasonable approach to improving the delineation of diverges in work zones would be to enhance the differences between paths (e.g., exit ramps vs. through lanes) without negatively impacting the ability of the delineation system to isolate the active roadway from work areas. These changes could be associated with shape, size, color, or reflective characteristics of the delineators or by changes in overall system characteristics (e.g., progressive coordination of flashing signals, as is the case for runway approach lights).

1.2 Research Objective and Tasks

As this study was undertaken, it was not readily apparent which approach or collection of approaches from the large range of possibilities would prove most effective at improving work zone diverge delineation. For this reason, as well as the high cost and potential hazards associated with field evaluation, the research team decided to focus on testing under laboratory conditions in a "virtual" environment. This method allowed for testing of a variety of driver reactions under a range of simulated environmental conditions before committing to the expense of field testing in follow-on studies. This study comprised the following tasks:

- Review of the relevant literature concerning the safety implication of diverge delineation methods in work zones
- Development of an array of potential improvements in delineation of work zone diverges while maintaining driver expectancy
- Design and implementation of a series of laboratory experiments to evaluate the potential for success of these proposed improvements
- Performance of statistical and interpretive analyses of the results of these experiments

1.3 Report Organization

This final report summarizes the efforts involved in the above tasks, including the results from the statistical and interpretive analyses, and includes data-based recommendations regarding how delineation of diverges in work zones may be improved. The report is structured to reflect the sequential findings from the major tasks above. Chapter 2 presents the comprehensive literature review. Chapter 3 describes the study methodology and alternatives considered. Chapter 4 provides results from, and statistical analysis of, the three experiments conducted to evaluate the effectiveness of the current delineation methods and a proposed delineation method. Chapter 5 discusses the results and provides recommendations for future study and implementation.

2 Literature Review

2.1 Safety

Road safety is a serious problem both within the United States and globally. In 2011, there were more than 5.3 million police-reported crashes in the United States and 33,367 fatalities (NHTSA 2013). The United Nations estimates that worldwide nearly 1.3 million people die in traffic crashes each year (United Nations 2011). While research shows that drivers operate their vehicles in a manner that they perceive to be safe (Theeuwes and Godthelp 1995), all elements of the roadway system, including traffic control systems and the roadway itself, impact their safety.

2.1.1 Factors to Consider

Although this report focuses on the design and placement of traffic control devices, work zone safety will also be influenced by any other safety issues found at the diverge locations. While not directly discussed in this report, these other factors must be considered in the successful design of a work zone. These considerations include, but are not limited to, annual average daily traffic (AADT) (Khorashadi 1998, Wang, et al. 2011); left-hand vs. right-hand exit (Chen, et al. 2011); ramp type (e.g., loop vs direct) (Khorashadi 1998, Lu, Geng and Chen 2010); deceleration lane length (Khorashadi 1998, Wang, et al. 2011); presence of lane drops and option lanes (Wang, et al. 2011); shoulder width (Wang, et al. 2011); on-ramps vs off-ramps (Khorashadi 1998, McCartt, Northrup and Retting 2004); and traffic speed and congestion (McCartt, Northrup and Retting 2004). Further work has also compared nighttime and daytime work zone operations (Ullman, Finley and Bryden 2008).

2.1.2 Fatal Crashes in Work Zones

Work zones are visually intense, complex environments that warrant special attention in safety research. Within the work zone, drivers are often required to interact with unfamiliar traffic patterns and devices that indicate the presence of roadway hazards. Khattak, Khattak, and Council (2002) estimated that there are approximately 24,000 non-fatal injury crashes and 52,000 property damage-only crashes in work zones annually within the US. The Fatality Analysis Reporting System maintained by the National Highway Traffic Safety Administration (NHTSA) reports that for 2010 at least 576 fatalities (2% of total reported fatalities) occurred in work zones. Since much less than 2% of vehicle activity occurs in these areas, work zones are significantly over represented in fatal crashes, at least at the national level.

This over-representation of fatal crashes within work zones is also observed within the State of Georgia. Daniel, Dixon, and Jared (2000) found an increase in fatal crash rates in Georgia work zones. These investigators found that although work zones make up a relatively small percentage of overall roadway mileage, those miles account for more fatal freeway crashes than in the areas

without road work on a per-mile basis. Additionally, nearly half of all crashes in work zones were single-vehicle collisions, and 12.1% of those crashes were rear-end collisions. These proportions can be compared with 56% single-vehicle and 5% rear-end crashes in non-work zone fatal crashes. These results indicate that drivers in work zones tend to have fewer single-vehicle loss-of-control crashes and more rear-end crashes.

Interestingly, most work zone crashes occurred when the work zone was idle. The type of construction was typically resurfacing or roadway widening. These findings suggest that inactive and relatively common work zones, which drivers may perceive as being lower risk, could lead to a number of fatalities. Additionally, the presence of equipment and workers may assist drivers in identifying work zone locations. This latter possibility was also examined as a portion of this research.

2.1.3 Work Zone Intrusions

When considering diverges, work zone intrusions are of significant concern as drivers are seeking to depart from the current roadway from a point within the work zone. The decision to exit is, in effect, a decision to intrude into the work zone *at the proper location*. Bryden, Fortuniewicz, and Andrew (2000) evaluated 290 work zone intrusions occurring between 1993 and 1998 in New York State. Of the observed intrusions, 10 occurred when drivers were trying to cross the work zone to enter or exit “a driveway or other roadside location.” While this type of incident is rare, their study demonstrated that work zone intrusions are an issue and suggested that there is room for improvement in delineation methods. Further, it was noted that only one of the incidents occurred when the work zone was separated from the travel lanes by a portable concrete barrier (PCB), indicating that such barriers could effectively reduce intrusion events.

While there is guidance available for work zone design (Roadway Safety Consortium 2010), most existing guidance is primarily concerned with maintenance activities. The MUTCD (*Manual on Uniform Traffic Control Devices*, FHWA 2009) also provides significant material on work zone design (Part VI), although most of the configurations provided represent “typical” applications with the caveat that “not every situation is addressed.” Many States have State-level materials (discussed in Section 2.3) to assist with the development of temporary traffic control plans, but these resources are largely regulatory in nature rather than provisions for detailed design guidance.

2.2 Work Zones

2.2.1 Channelizing Devices in Work Zones

Work zone channelizing devices are regulated by the Federal Highway Administration through its *Manual on Uniform Traffic Control Devices* and have been largely standardized across the

United States (FHWA 2009). However, particularly with temporary channelizing devices, little research was performed prior to standardization of many of these devices to determine if drivers consistently understood their meaning. Pain, McGee, and Knapp (1981) explain:

> *"Devices described in Part VI of the* ***Manual on Uniform Traffic Control Devices*** *(MUTCD), have developed simply as an evolvement from other devices, rather than as a result of scientific testing as to what best stimulates driver awareness of work zone situations."*

For instance, the nearly ubiquitous "channelizing drum" patent was not filed until 1976 (Kulp and Florsheim 1978). At that time, this plastic drum was deemed a safer alternative than the filled metal 55-gallon drums previously in use. However, prior to the patent, little research was conducted to explore how drivers interpret the device. Some research has been found that was carried out after the patent filing, such as a discussion of the visibility characteristics of the drums (Pain, McGee and Knapp 1981).

Recent research. Modern research into channelizing devices has largely focused either on comprehension of existing systems or crashworthiness. Several studies have investigated driver performance related to use of different devices in work zones. Finley et al (Finley, Ullman and Dudek 2001) investigated how sequential flashing lights placed on top of drums aided driver comprehension of a lane closure. They used a traditional survey to evaluate driver understanding after the participants drove through the scene. Later, Finley, Ullman, and Trout (2006) showed drivers static images of mobile painting operations to evaluate comprehension of signs. They used a questionnaire to evaluate the use of "Your Speed/My Speed" signs on the back of slow moving trucks, and they found that drivers were confused by the two sets of numbers.

Pain, McGee and Knapp (1981) performed several experiments investigating driver performance related to channelizing devices in freeway work zones. These investigators measured speed, lane position, identification distance, and other performance measures along a freeway lane closure. Experiments were conducted using instrumented vehicles on a freeway lane closed to other traffic. They found that channelizing devices are largely interchangeable, but lights should be used at night to increase visibility. They also performed a series of tests using a tachistoscope (device that presents images for a set time) to present flashing patterns with various orange and white ratios to determine ideal size and pattern of striping on channelizing devices. The results of these studies were the patterns of orange and white stripes currently in use on temporary traffic control devices.

Temporary barriers. Work zone research has also focused on temporary barrier walls and their impact on driver performance in work zones. Finley, Theiss, et al. (2011) compared driver performance in the presence of traditional drums and plastic barriers (referred to as "longitudinal channelizing barricades" or LCBs in their study). They found that drivers on a test track were

less confused at diverges indicated with LCBs, drivers identified lane closures when they were used, and drivers preferred LCBs for delineating open driveways in work zones. This corroborates anecdotal data from state DOT officials who said that LCBs should be used when there is a need to "provide more path guidance."

Officials were mostly concerned, however, with the cost of temporary barriers. Iragavarapu and Ullman (2012) reiterate this cost issue, finding that portable barriers are only cost effective on high-speed roadways (with operating speeds of 70 mph) with high volumes (around 40,000 vehicles ADT for a yearlong project) where work is occurring close to the travel lanes. However, cost aside, portable barriers are effective at preventing intrusion, as seen in Bryden, Fortuniewicz, and Andrew (2000). In that study only concrete barriers were considered. Of the 290 observed intrusion collisions in New York State, only one occurred where portable barrier walls were used.

2.2.2 Diverges in Work Zones

As previously mentioned, Finley, Theiss, et al. (2011) compared driver performance resulting from the use of drums and portable concrete barriers in work zones. They used a combination of simulation scenes and closed-course roads to gauge driver understanding and recognition of a temporary "exit ramp" constructed of (1) drums, (2) PCBs, or (3) a combination of both. The study found that the drivers performed best with the "all-barrier" alternatives and had the most difficulty with an "all-drum" alternative. The mixed drum/barrier alternatives resulted in driver performance between these extremes, and a configuration having barriers only at the tapers of the ramp had the best performance among these mixed alternatives. The alternatives tested were for ramp openings at the diverge point of either 120 ft. or 240 ft. with continuous barriers and/or drums spaced 20 ft., 60 ft., or 120 ft. apart (depending on the alternative considered) providing the delineation of this diverge. Interestingly, for the smaller (120 ft.) opening, reducing the drum spacing from 120 ft. to 60 ft. resulted in poorer driver performance by reducing the distance-to-recognition. Lengthening the ramp opening from 120 ft. to 240 ft. increased the identification distance of the diverge. Using portable concrete barriers also improved distance to recognition over all-drum delineation.

2.3 Agency Standards

2.3.1 Federal Standards

The *Manual on Uniform Traffic Control Devices* (FHWA 2009) offers guidance regarding work in the vicinity of freeway interchanges, but it does not include standards specific for exit ramps. The guidance in Section 6G.17 (Interchanges) states:

> *Access to interchange ramps on limited-access highways should be maintained even if the work space is in the lane adjacent to the ramps. Access to exit ramps*

> *should be clearly marked and delineated with channelizing devices. For long-term projects, conflicting pavement markings should be removed and new ones placed. Early coordination with officials having jurisdiction over the affected cross streets and providing emergency services should occur before ramp closings.*

The MUTCD also includes a "typical application" for work near an exit ramp (Figure 2-1). In this configuration, the taper length is determined by the speed limit and the lane width; however, it does not specify any special spacing for the channelizing devices. For general conditions, the MUTCD recommends that channeling devices should be spaced a distance in feet equal to the speed limit in mph (i.e., 50 ft. for 50 mph) for tapered sections and twice that distance (i.e., 100 ft. for 50 mph) for tangent sections. It is interesting to note that the dimensions found in Figure 2-1 are not geometrically possible given these recommendations. That is, to maintain the suggested 600 ft. per lane taper length (12 ft. lane width multiplied by speed) for a 50 mph facility and a 100 ft. exit opening, a 12 ft. ramp lane width is not possible.

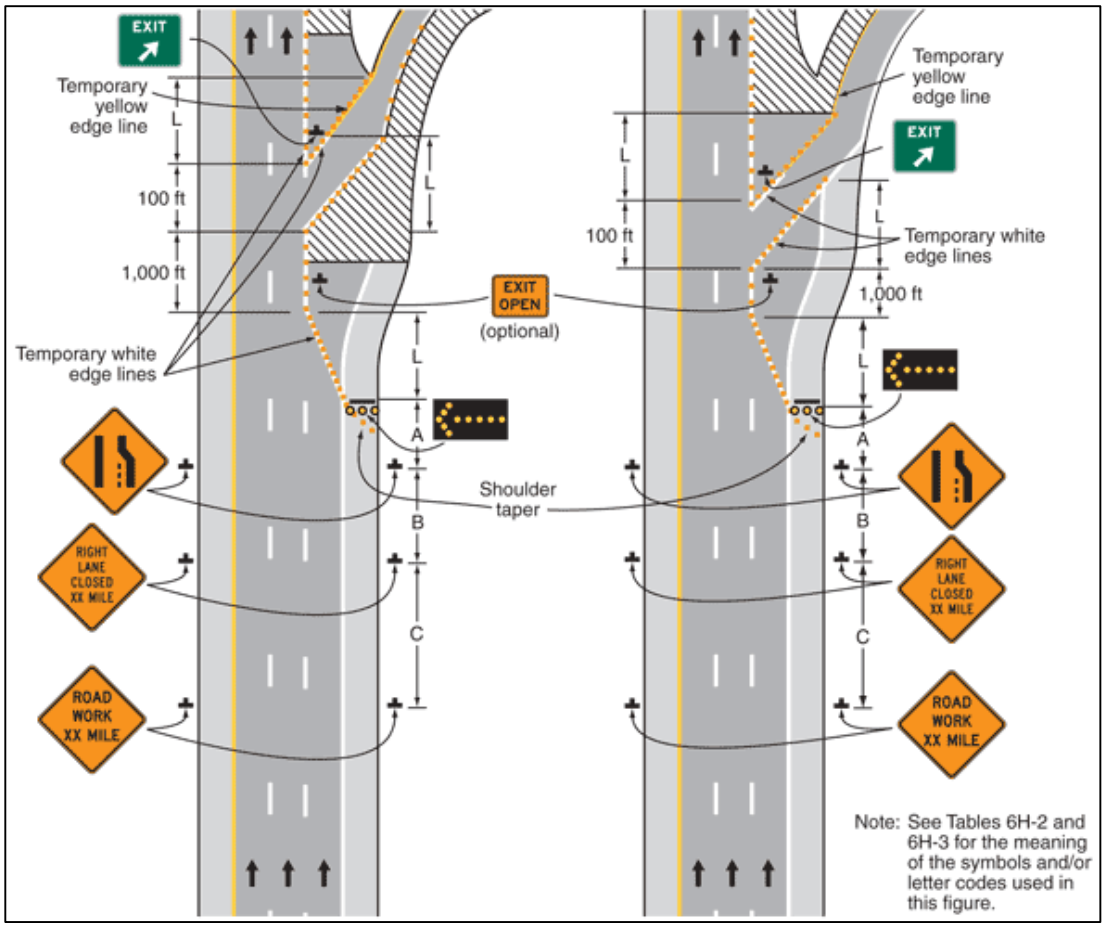

Figure 2-1 MUTCD Typical Application 6H-42 (FHWA 2009)

2.3.2 State Standards

There are several states that specify standards for diverges in freeway work zones beyond those found in the MUTCD. Examples of these standards for the States of Michigan, California, North Carolina, and New York are described below. A number of other states, including Florida, have specifications that imply spacings that are more conservative than the MUTCD, such as requiring a closer spacing of drums or specifying taper lengths that are less dependent on speed limits.

Michigan. The State of Michigan (Michigan DOT 2008) has extensive standard drawings that specify temporary traffic control devices and configurations. While the Michigan specifications do not include minor diverges at service interchanges, they do specify temporary traffic control for major diverges at system interchanges (Figure 2-2). Specifications for this condition call for channelizing device spacing of a maximum of 45 ft. in tapers and 90 ft. in tangent sections. Michigan's standards vary from the MUTCD's typical application (regarded as guidance, not a standard) by specifying a diverge lane width (15 ft.) and a taper rate rather than specifying a minimum ramp opening length. The taper in that section is specified as a minimum of ½ L (L = speed limit × lane shift in feet), which is half the MUTCD guidance. A portion of Michigan's standard configuration (not to scale) is presented as Figure 2-2.

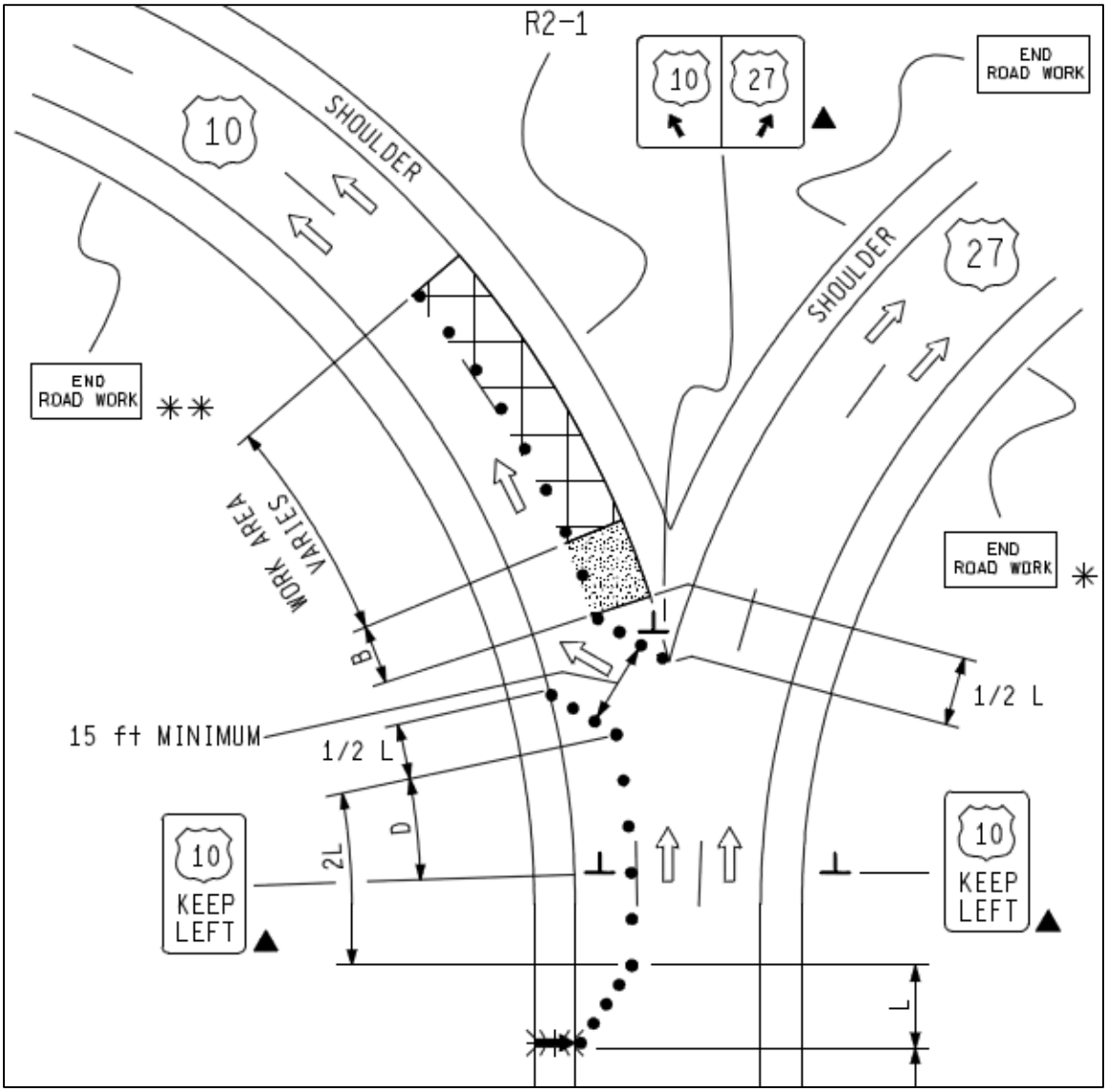

Figure 2-2 Michigan Diverge Standard Highlighting Ramp Area Drawing M1420a (Michigan DOT 2008)

California. The State of California (CalTrans) specifies channelizing device spacing at minor diverges and along standard lane closures. California's standard (CalTrans 2006) calls for 100 ft. spacing between devices along tangent sections of a freeway lane closure and 50 ft. maximum spacing in the vicinity of the ramp (Figure 2-3). Although the drawings appear to show the 50 ft. spacing beginning 120 ft. before the taper and extending 200 ft. after the taper, the drawings are not to scale and the accompanying notes do not expressly call out the distance to start the taper. The California standard does, however, expressly specify that for every 2000 ft. along the tangent section of a lane closure, 3 drums must be placed perpendicular to the traveled way, presumably to reinforce driver perceptions that the lanes are closed.

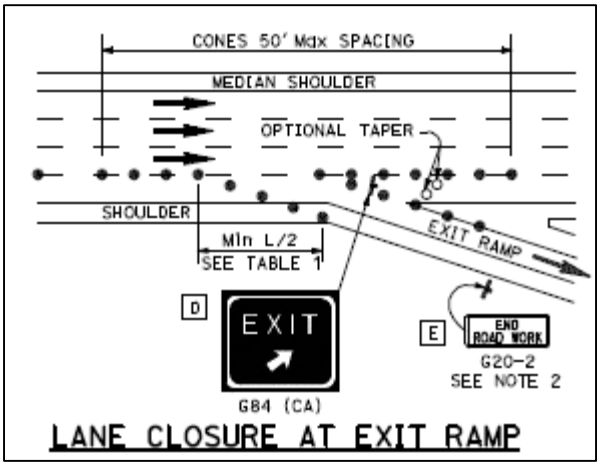

Figure 2-3 California Diverge Standard Highlighting Ramp Area Sheet T10 (CalTrans 2006)

North Carolina. The North Carolina Department of Transportation standard specifications (North Carolina DOT 2006) call for the use of more channelizing devices at a diverge than any other specification reviewed (Figure 2-4). North Carolina's standards call for 10 ft. spacing between drums from 100 ft. prior to the diverge to 100 ft. after the diverge. In the tangent sections, spacing is allowed to be two times the speed limit in feet, which for a 60 mph road would be farther apart than the California, Michigan, or Florida standards. North Carolina specifies a minimum of 200 ft. for the length of the ramp opening. The taper length and type varies based on the location of the work zone relative to the ramp opening; the standard specifies a minimum of 120 ft. for a taper if work is downstream of the ramp, and it uses the same formula as the Michigan specification (½ L [L = speed limit × lane shift in feet]) if the work is upstream of the ramp.

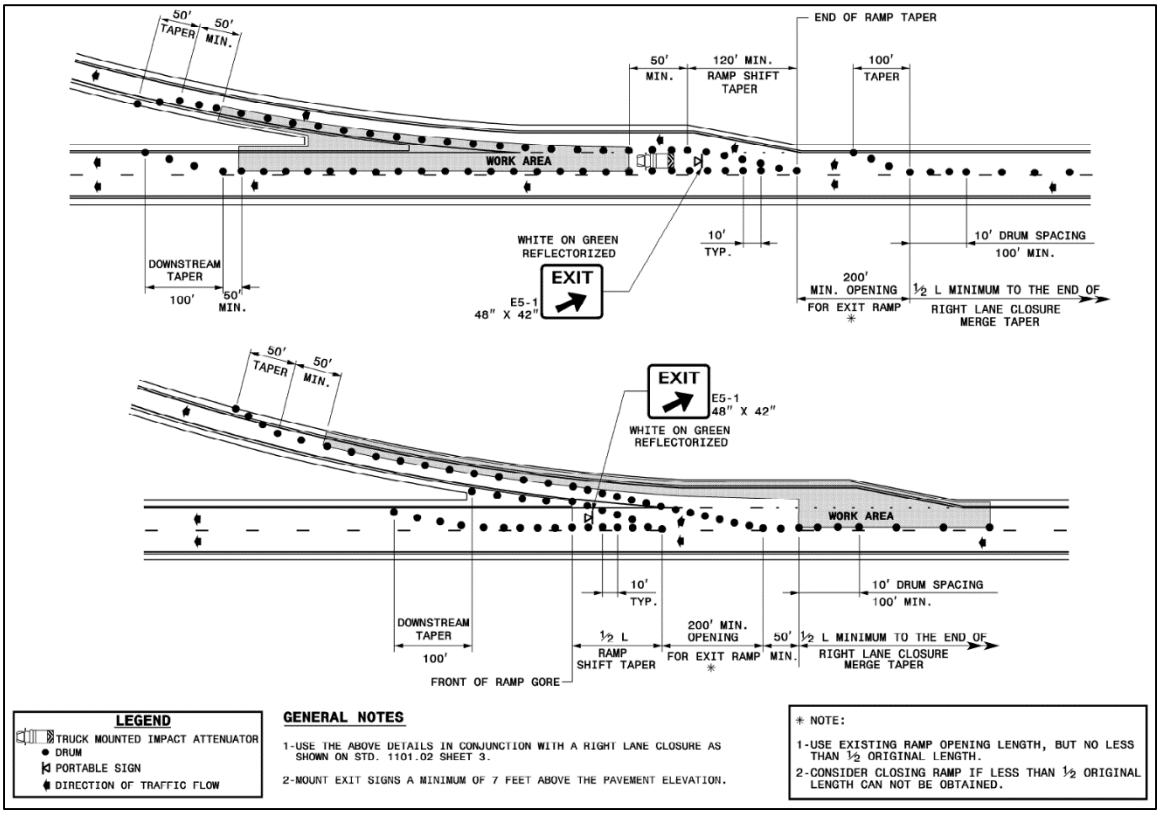

Figure 2-4 North Carolina Standard for Work near Exit Ramps 1101.01 Sheet 7/9 (North Carolina DOT 2006)

New York. In contrast with the other states discussed, New York State (NYSDOT 2008) does not differentiate between tapers and tangent sections within their work zone specifications. Their standard states that channelizing devices spacing "shall not exceed 40 ft. center to center" throughout an active work zone (Figure 2-5). New York also mandates taper lengths of L feet, compared with the ½ L of the Michigan and North Carolina standards.

Florida. Finally, unlike the other states discussed, the State of Florida does not give any specific constraints for diverges. Rather Florida requires that for roadways with speed limits of 50 mph to 70 mph (typical within freeways), channelizing devices should be placed no more than 50 ft. apart in tapers and no more than 100 ft. apart in tangent sections (Florida DOT 2012).

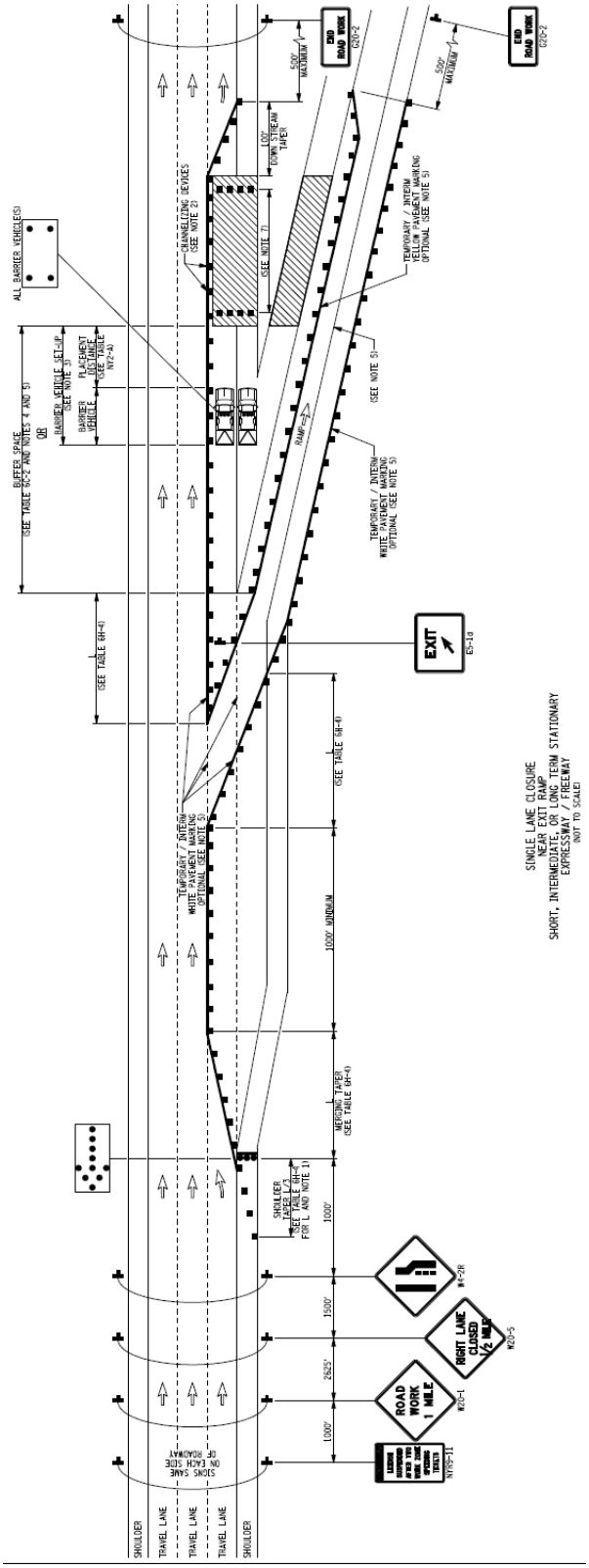

Figure 2-5 Portion of New York State Diverge Standard Highlighting Ramp Area Sheet 619-34 (NYSDOT 2008)

2.4 Human Perception of a Path: The Principles of Grouping

As discussed earlier, previous studies have shown that using linear channelizing devices, such as portable concrete barriers, is often considered the most well-defined (as it is typically a continuous device) and the safest (as it provides protected separation from the work zone) way to separate the traveled way from the active work area in a work zone. However, both cost and time constraints frequently make this particular device impractical. Thus, arrays of more economical and rapidly deployable devices are regularly implemented in an effort to help drivers perceive a "single wall" of objects that is equivalent to the physical barrier created by such linear channelizing devices. The ability of humans to mentally create a "single entity" from an array of discrete "point" objects (e.g., orange and white drums) is described by the Gestalt principles of grouping, which were first identified nearly a century ago.

2.4.1 Gestalt Principles of Grouping

Gestalt principles are central to work zone traffic control in that this human ability to group objects enables discrete objects to delineate a path, including a diverge. These principles, first introduced in 1923 by Wertheimer, have been expanded on by many other researchers over the years. Recently, Johnson (2010) reviewed the six non-moving Gestalt principles of *Proximity, Similarity, Continuity, Closure, Symmetry,* and *Figure/Ground*. These principles are illustrated in Figure 2-6.

The principle of *proximity* states that individuals mentally group objects based on how close they are to each other. *Similarity* indicates that separate objects are grouped because they appear to be the same (in some manner) and other objects different. In a similar vein, the *figure/ground* principle indicates that individuals tend to group objects together based on a presence of a common background. The *closure* principle causes overlapping objects to appear to be grouped together and also allows separate objects to appear to be part of a single object. Similarly, and important for path identification, the *continuity* principle indicates that individuals will tend to group objects that have a linear pattern common to all objects in the group. *Symmetry* helps individuals group "wireframe" objects that overlap (Johnson 2010).

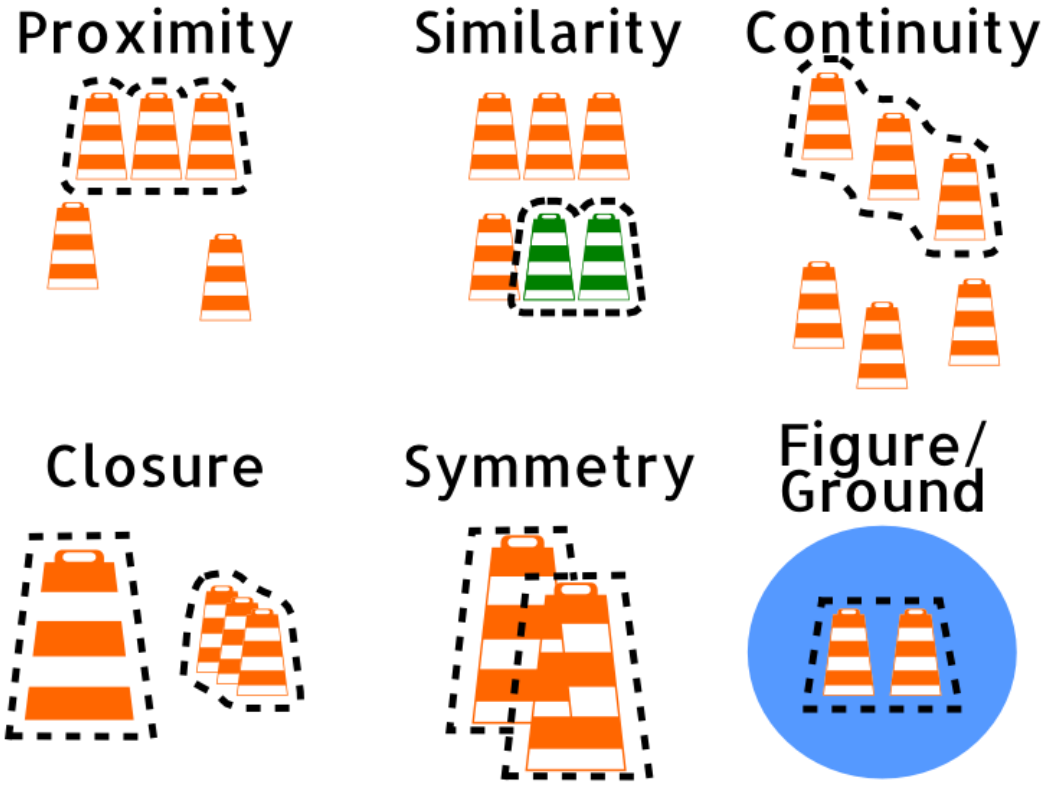

Figure 2-6 Gestalt Principles of Grouping (Groups Shown with Dotted Lines)

The effect that these principles have on human perception can significantly affect how an individual responds to stimuli in the world. In a series of five experiments, Coren and Girgus (1980) found that when some objects were grouped through Gestalt principles, the distances between objects in the group were perceived to be smaller than the distance between objects outside the groupings—even though the distances were identical. Perceived distances that vary from actual distances in a way that negatively impacts safety could have a profound impact on work zone design. O'Shaughnessy and Kayson (1982) further investigated these concepts in their testing by manipulating the duration that an individual was shown a scene. These investigators found that both proximity and duration had an effect on how accurately individuals assessed distances, with improved accuracy with smaller distances and with shorter times. They did not find the same effects with similarity and closure, however. This would tend to imply that although the Gestalt principles are good heuristic guidance, they cannot be applied as laws; thus, testing is still necessary to predict human performance.

2.4.2 Application to Work Zones

In work zone traffic control, these Gestalt grouping principles may help drivers interpret a collection of point-based channelizing devices as a single entity. In addition, these grouping principles could help identify potential issues in current work zone delineation practices. For example, there is no consensus among agencies as to the appropriate level of *proximity* of delineation devices or even whether this value should depend upon the type of device being deployed. As discussed in Section 2.3.2, State DOTs set drum spacing standards at different intervals, and quite often the spacing varies within a state, as well. Furthermore, a variety of delineators, ranging from narrow post type to the common standard barrel, are in use *similarity*.

Similarly, *continuity* can be degraded due to variability in device placement or as a result of post-deployment shifting caused by wind or traffic. Likewise, arrays of drums or cones may appear to be closed (*closure*) when viewed at a distance because they overlap in the driver's field-of-view. However, as the driver draws nearer, the overlap may be lost and the closure compromised, thereby shifting the burden of grouping to the other Gestalt principles. Unique to diverges, *similarity* can actually create a problem for drivers because there are two appropriate and safe traveled ways (the main road and the ramp) indicated using the same devices.

3 Methodology

3.1 Overview

In conducting any form of research, especially that involving highway safety, it is essential to reduce to the lowest level possible the risks to the general public, volunteer participants, and the investigators themselves. These considerations, as well as the cost of field research, dictated that the evaluation of the effectiveness of delineation devices in this study take place under laboratory conditions. In the chosen experiment method, the research team used a brief view of a still image (scene) to test volunteer participants' ability to identify the location and condition (i.e., open or closed) of a ramp diverge within a freeway work zone. The images were varied to reflect various work zone configurations, distances from the ramp, and types and spacing of delineation devices used.

3.1.1 Participants and Protocols

Since this study used human subjects, all experimental protocols were vetted and approved by the Human Subjects Institutional Review Board (IRB) for both the Georgia Institute of Technology and Morehead State University. All investigators involved in conducting the experiments and the subsequent analysis of the data were trained and certified for the conduct of Human Subjects Research to U.S. Department of Health and Human Services standards.

Study participants were recruited from the pool of students in an introductory psychology course at either the Georgia Institute of Technology in Atlanta, Georgia, or Morehead State University in Morehead, Kentucky. As an elective, this course includes students from departments across each campus. Participants were excluded from participation if they had not held a valid driver's license for at least two years. Each university uses the same online system for managing participation in human-related studies. Students in each experiment were given credit for one hour of their time for participating in this study. Demographic information was not collected.

For this study three sequential experiments were conducted, with different participants, over the project duration. In each experiment participants were shown a variety of scenes that varied features such as roadway geometry, ramp condition, roadside vegetation, placement of construction equipment, and work zone traffic control devices and layout patterns. Each image shown to the participants contained a diverge area, either within a work zone or a base case with no work zone. Multiple alternative channelizing devices and layouts were provided (e.g., drums at different spacing, barriers, etc.) in each set of images shown to the participants. After viewing each image, participants were asked to indicate if the ramp was open or closed and, if open, to identify the location of the ramp entrance. The accuracy of the participants' responses in

identifying the ramp location and condition (open/closed) were subsequently analyzed to determine the effectiveness of the particular treatment for delineation of the ramp.

3.1.2 Experimental Series

Over the course of the study, each set of tests incorporated knowledge gained from the previous experiment. The three experiments are described as follows:

Experiment 1 – Tested existing channelizing devices and layouts in an uncluttered environment at five different distances from the ramp. This experiment evaluated the participant's (driver) perception (location and condition) of the ramp while limiting the influence of potential confounding factors not related to the channelization devices themselves (e.g., presence of construction equipment, roadside vegetation, signage, etc.).

Experiment 2 – Provided additional investigation into potential findings from the first experiment, such as the impact of minor device misalignment. In addition, this experiment added a new channelizing device (the Linear Channelizing Device) developed in this study to address driver (participant) errors observed in Experiment 1.

Experiment 3 – Evaluated selected channelizing devices in environments with various roadside vegetation and construction equipment combinations, increasing scene complexity to better reflect potential field conditions.

Figure 3-1, Figure 3-2, and Figure 3-3 provide example images used in Experiments 1, 2, and 3, respectively.

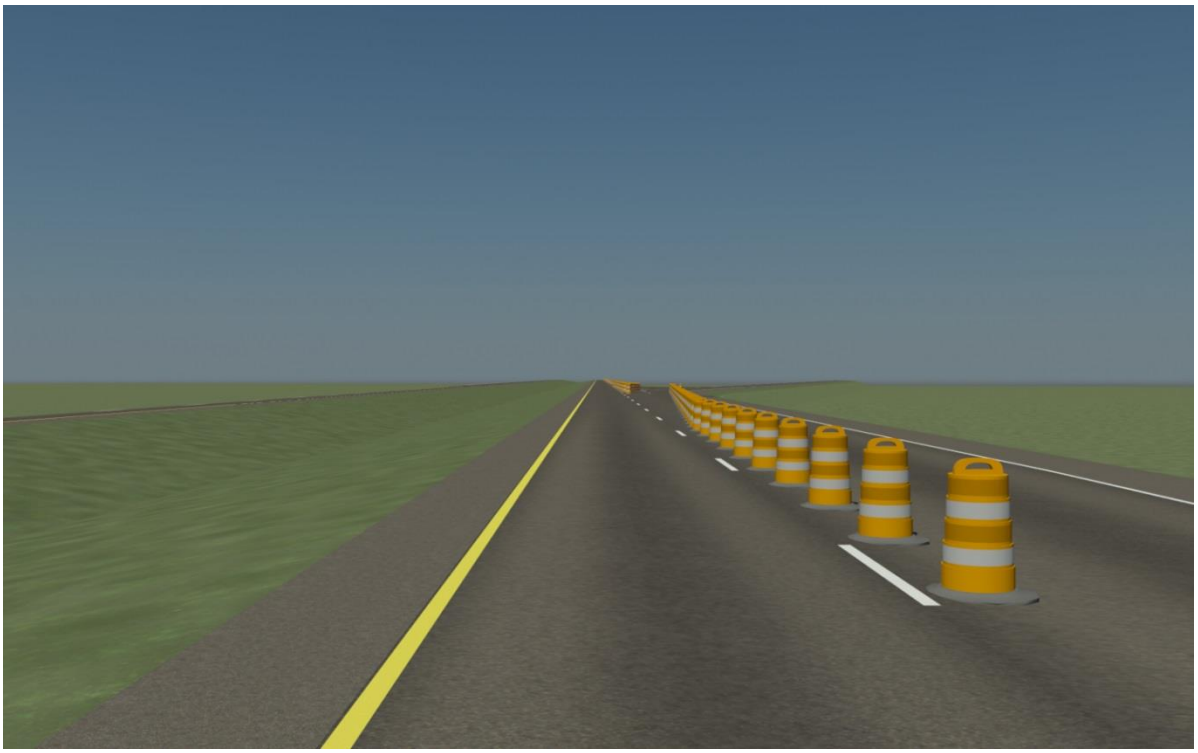

Figure 3-1 Example Experiment 1 Rendering: Drums 10 ft. Apart, Ramp Open, Straight Freeway Alignment, 1 Second Travel Time to Diverge

Figure 3-2 Example Experiment 2 Rendering: LCD, Ramp Open, Straight Freeway Alignment, 1 Second Travel Time to Diverge

Figure 3-3 Example Experiment 3 Rendering: Ramp Closed, Straight Alignment, Roadside Vegetation and Construction Equipment Present

3.2 Virtual Environment Development

The base roadway layout for the experiments was designed to match common rural freeway and work zone specifications used in the State of Georgia. The specific criteria used for these layouts are provided in Table 3-1. Curve radii were taken from AASHTO standards (AASHTO 2011, 6th edition) with a super elevation rate of 8%. To eliminate potential secondary visual cues that could indicate ramp location, all grades were flat and no bridges were included.

Three virtual highway alignments were developed:

1) Freeway with a horizontal curve to the left (R=1810′) and a right-hand side taper-type ramp alignment matching the upstream freeway tangent

2) Straight freeway alignment with parallel deceleration lane for right-hand side ramp

3) Freeway with a horizontal curve to the right (R=1810′) and a right-hand side taper-type ramp

In order to create a simple visual scene that minimized possible distractions, the virtual environment included only a grass texture with a cloudless sky, except where a specific vegetation was included as part of a test scenario (found in Experiment 3). Similarly, while

standard striping was used, all signs were removed from the scene to focus participants' attention on the channelizing devices.

Table 3-1 Roadway Design Standards for Virtual Environment, Representative of Rural Freeways in Georgia

Design Element	Measurement
Lane width	12 ft. (3.6 m)
Outside paved shoulder	10 ft. (3.0 m)
Inside paved shoulder	4 ft. (1.2 m)
Median width	64 ft. (19.5 m)
Roadway design speed	70 mph (112.7 km/h)
Ramp design speed	50 mph (80.5 km/h)
Ramp taper	4 degrees
Final ramp angle	15 degrees
Work zone speed limit	60 mph (96.6 km/h)
Drum spacing in advance of diverge	120 ft. (36.6 m)

Each of the virtual roadways was designed using AutoCAD Civil 3D®. The resulting three-dimensional design model was exported to a companion product (Autodesk 3DS Max®) for refinement and rendering of the final images. Each image was rendered using the Mental Ray® renderer at a resolution of 1680 × 1050 pixels. Images in Experiments 1 and 2 were loaded as bitmap image files. The volume of images in Experiment 3 necessitated JPEG compression; there were no visible artifacts or apparent loss of detail.

3.3 Linear Channelizing Device Design

Analysis of results from Experiment 1 highlighted continuity and closure as critical aspects of channelization (discussed in detail in Section 3.4). Based on those results, the research team developed a device for virtual testing that incorporated those principles without requiring the physical size of a portable concrete barrier (see Figure 3-4 Illustration of the Linear Channelizing Device).

The design of the Linear Channelizing Device (LCD) was based on existing devices in the field, such as the MUTCD-defined "Temporary Lane Separators" (FHWA 2009, MUTCD 6F.72), as well as the engineering judgment of the project team. The base of the device has an overall trapezoidal configuration with a bottom width of 2 ft. (60 cm) in contact with the pavement. The two sloping sides are each 9 inches wide and colored orange. The top surface is colored white and is 6 inches wide. The color scheme was developed using MUTCD standard colors to simulate a white lane edge line combined with orange to indicate construction. The rise in the

sloped section is 3 inches, based on GDOT Standard 9032B (GDOT 2011) for a “Raised Edge with Concrete Gutter.” These raised edges are allowed for use on high speed arterials and freeways.

The visibility of the trapezoidal base is augmented by the periodic introduction of vertical pylons. The pylon design followed the specifications outlined in Section 6F.65 Figure 6F-7 of the MUTCD, “Tubular Markers” (FHWA 2009). The material of the Linear Channelizing Device is not specified since it has only been represented virtually, though it is intended to be highly flexible when traversed, thus providing minimal to no physical resistance to impact.

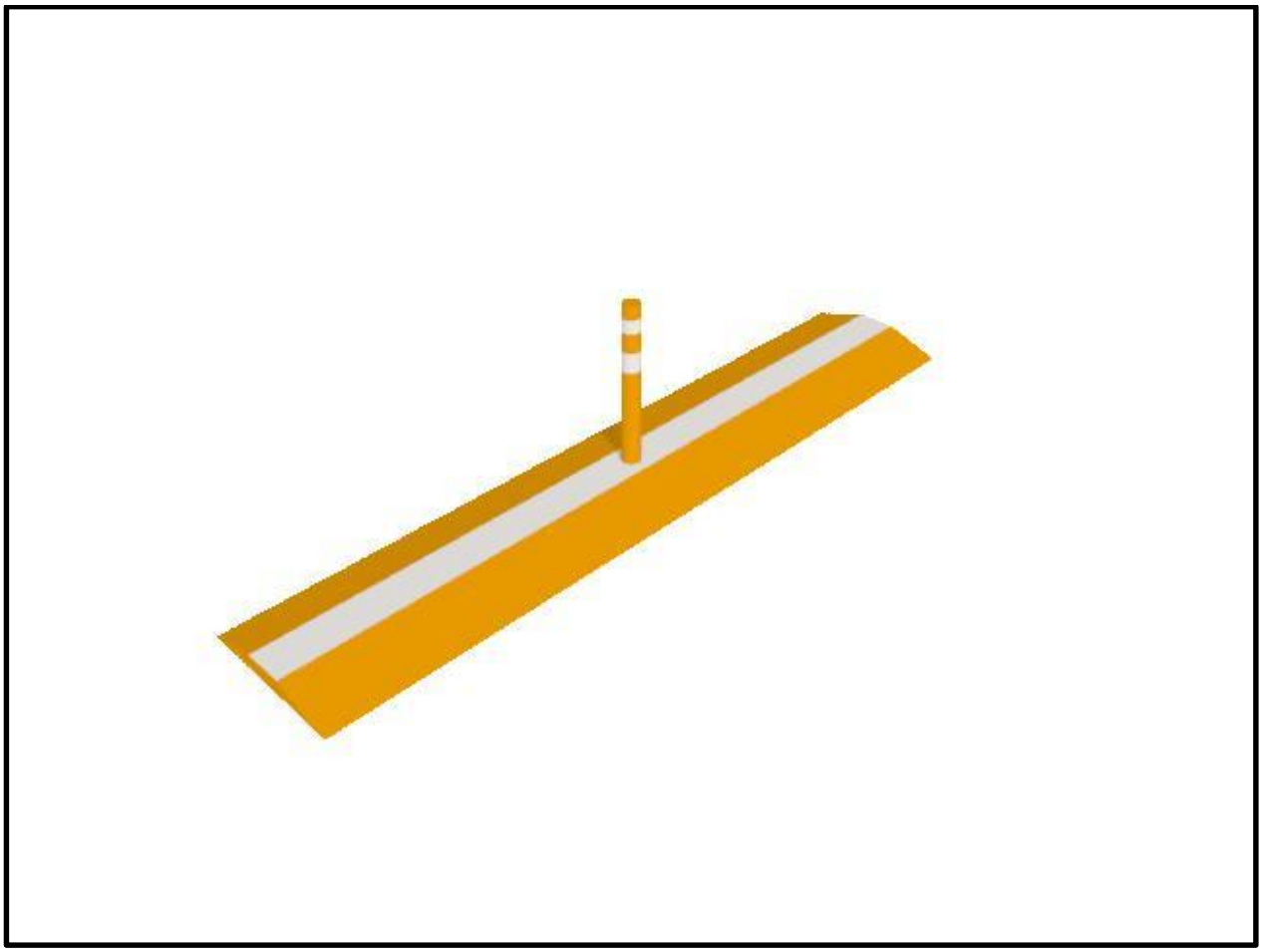

Figure 3-4 Illustration of the Linear Channelizing Device

3.4 Experiments

For each experiment, participants were seated at individual computer workstations. After some brief comments from the proctor and a few introductory slides to familiarize the participants with the computer configuration, the experiment began.

During the course of each experiment, participants were shown a series of static images and asked to identify if the ramp displayed was open or closed to traffic. If the ramp was open, they were asked to move the cursor to the ramp location and click the left mouse button. If the ramp was closed, the participants were asked to identify this condition by clicking on the “Exit Closed” icon on the lower left corner of the image (Figure 3-5). In Experiments 2 and 3, an additional “Don’t Know” icon was added to the top left of the image to allow participants an additional response option.

Between images, participants were asked to click in a region on a transition image (Figure 3-6) to return their mouse cursor to a consistent starting position. Having a fixed intial cursor position allows for consistent measurement of response latency (i.e., time from initial image display to participant response) that can also be used in analysis of participant responses. If, for any reason, a participant did not respond to an image within an allotted time (3 seconds in Experiment 1 or 3.5 seconds in Experiments 2 and 3), the image would time-out and the transition image would be displayed. Conversely, the transition image would not time-out, and the participants were required to click on the + sign (see Figure 3-6) to exit the transition image.

As described previously, each test image showed a particular freeway alignment with a ramp and a work zone defined by delineation devices in one of the various configurations. (The only exception to this was a base case image that did not include a work zone.) In one-half of these images the ramp was closed. The number of delineation device configurations and time-to-exit locations (i.e., travel time from the image view point to the beginning of the diverge taper) varied by the experiment, as did the number of replicate images. However, the total number of test images shown in each experiment was restricted to a range of 800 to 1000. Within an experiment all participants were shown the same images before and after a rest period, though the image order during each time period was randomized for each participant. The overall time required varied by participant, but it ranged from less than 45 minutes to a maximum of 1 hour. A more detailed description of the images used in each experiment is provided in the next section.

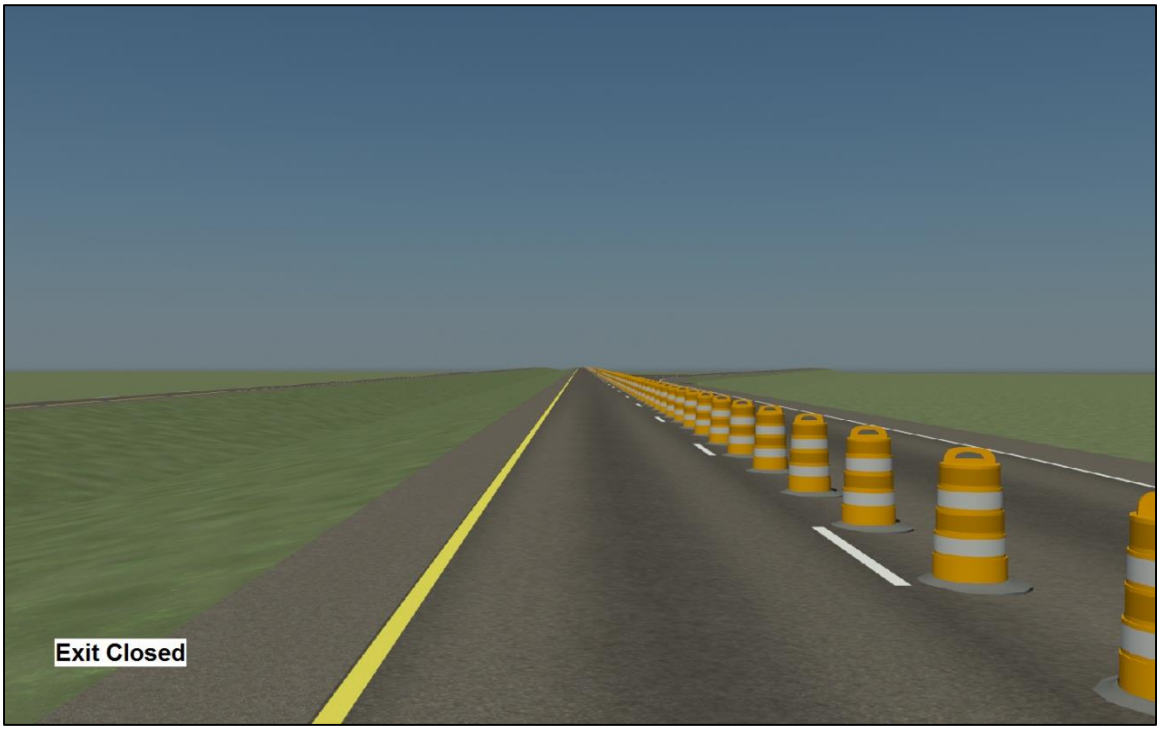

Figure 3-5 Image with "Exit Closed" Icon

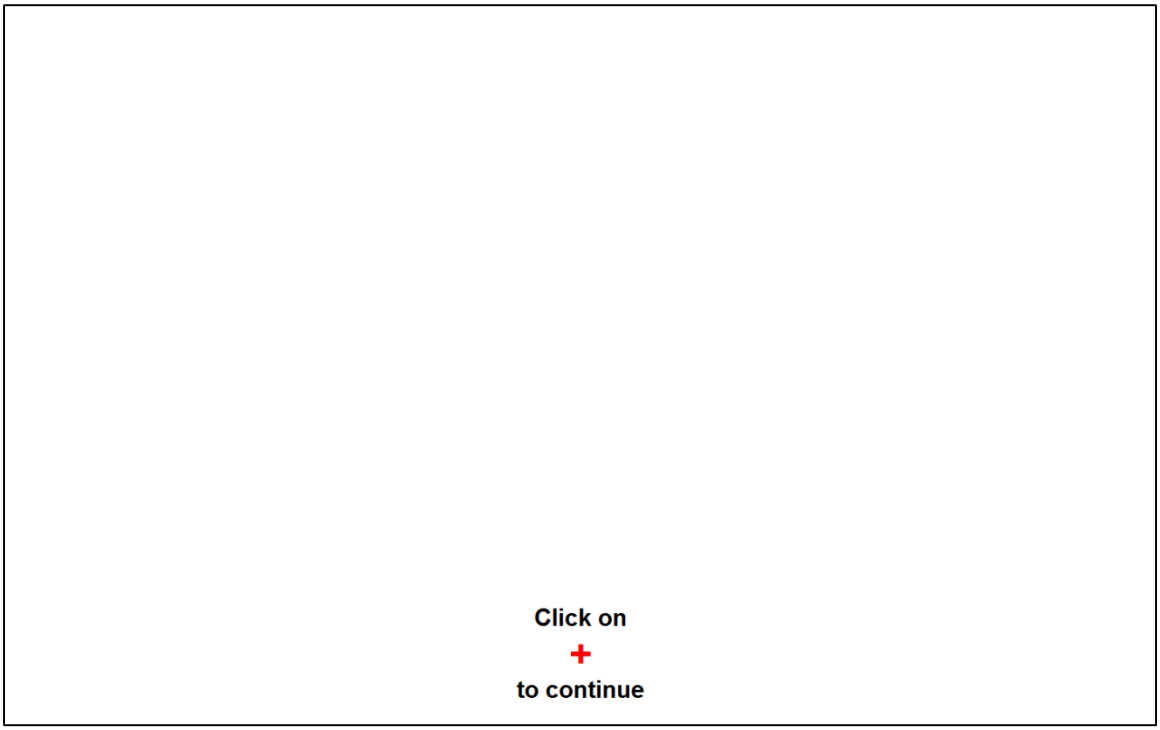

Figure 3-6 Transition Image between Roadway Images

3.4.1 Experiment 1: Existing Channelizing Devices

In this experiment, participants were shown rendered static images of ramps configured using various combinations and configurations of existing delineation and channelization devices. This experiment was designed to examine a broad range of existing devices, roadway geometries, and time-to-exit distances. This broad experiment had two principal objectives. The first objective was to provide a preliminary evaluation of the limitations of existing delineation treatments and from that explore possible design principles that could be used to develop new devices or methods for overcoming these limitations. The second objective was to evaluate the roadway geometries and time-to-exit distances that could best be used to evaluate more complex conditions later in the project. Experiment 1 explored the following features:

Delineation/channelizing devices at diverge:

- Drums spaced 40 ft. apart
- Drums spaced 10 ft. apart
- Drums spaced 40 ft. apart with up to 2 ft. of random placement error
- Portable concrete barriers

Geometries:

- Taper type exit with freeway alignment straight
- Taper type exit with freeway alignment curve to the left

Times-to-exit (travel time at 60 mph to the beginning of the diverge taper):

- 5 seconds from the diverge taper
- 4 seconds from the diverge taper
- 3 seconds from the diverge taper
- 2 seconds from the diverge taper
- 1 second from the diverge taper

Ramp Condition:

- Open
- Closed

In addition, an Open Ramp condition for a “No Work” configuration was included as a control. In all work zones with drums, a 120 ft. spacing was utilized upstream of the diverge.

A static image was generated for each channelizing device configuration (four alternatives), geometry (two alternatives), time-to-exit (five alternatives), and ramp condition (two alternatives) combination, for a total of 80 distinct images. Furthermore, a No Work static image was generated for the open ramp condition for each time-to-exit and road geometry for a total of 10 additional separate images. Ten replications of each static image were generated, resulting in

a total of 900 images shown to each participant. For each participant, five replicates (450 images) of each image were shown, followed by a rest period and then an additional five replicates (450 images). As stated, each set of 450 images was presented in a different random order to each of the participants. The rest periods were of variable duration, from a few minutes to 10 minutes. The maximum duration of the experiment was one hour. Most participants completed the experiment within 45 minutes.

3.4.2 Experiment 2: New Channelizing Device

Similar to Experiment 1, in Experiment 2 participants were shown rendered static images of ramps using various configurations of existing delineation/channelization devices. In addition, Experiment 2 included images that represented the new Linear Channelizing Device. As described earlier (Section 3.3), LCD was developed based on the results of Experiment 1. The primary purposes of Experiment 2 were to (1) evaluate LCD and (2) further examine the design principles assessed in Experiment 1 in a more focused setting. Experiment 2 explored the following features:

Delineation/channelizing devices at diverge:

- Drums spaced 40 ft. apart
- Drums spaced 40 ft. apart with up to 2 ft. of random placement error
- Drums spaced 40 ft. apart missing 10% with up to 2 ft. of random placement error (two variations)[1]
- Drums spaced 10 ft. apart
- Drums spaced 10 ft. apart with up to 2 ft. of random placement error
- Drums spaced 10 ft. apart missing 10% with up to 2 ft. of random placement error (two variations)[1]
- Portable concrete barriers
- Linear Channelizing Device
- Linear Channelizing Device missing 10% of posts

Geometries:

- Taper type exit with straight freeway alignment
- Taper type exit with freeway alignment curve to the right[2]

Times-to-exit (travel time at 60 mph to the beginning of the diverge taper):

- 5 seconds from the diverge taper (straight geometry only)

[1] To ensure that a single random configuration was not disproportionately impacting data, two random variations were included.

[2] Result not included from curve alignment, this will be discussed in Chapter 4.

- 3 seconds from the diverge taper (curved and taper geometry)
- 2 seconds from the diverge taper (curved geometry only)
- 1 second from the diverge taper (curved and taper geometry)

Ramp Condition:

- Open
- Closed

Furthermore, an open ramp condition No Work configuration was included as a control. As with Experiment 1, in all work zones with drums, a 120 ft. spacing was utilized upstream of the diverge

Also as with Experiment 1, images were generated for each delineation/channelization device, geometry, time-to-exit, and ramp condition combination, except as noted (e.g., 5 second time-to-exit only applied to the freeway straight alignment). Additionally, a No Work image was generated for the open ramp condition for each time-to-exit value. In total, 138 separate still images were created.

For the experiment, the participants were shown six replications of each image, resulting in a total of 828 images for which responses were recorded. For the channelizing device alternatives with missing posts or drums the six images were composed of three replications for each of two sub-alternatives. The images were presented in a random order for each participant.

Similar to Experiment 1, a rest period was provided at the midpoint. Again, most participants completed the experiment within 45 minutes.

3.4.3 Experiment 3: Varying Roadside Environment and Construction Equipment

To verify and expand the results from Experiment 2, various roadside vegetation and equipment combinations were added to the scenes to evaluate the impact of increasing the overall visual complexity of the scenes for a subset of conditions. Experiment 3 explored the following conditions:

Delineation/channelizing devices at diverge:

- Drums spaced 40 ft. apart
- Drums spaced 40 ft. apart with up to 2 ft. of random placement error
- Portable concrete barriers
- Linear Channelizing Device
- Linear Channelizing Device missing 10% of posts

Geometries:

- Taper type exit with straight freeway alignment

Times-to-exit (travel time at 60 mph to the beginning of the diverge taper):

- 3 seconds from the diverge taper
- 1 second from the diverge taper

Ramp Condition:

- Open
- Closed

Vegetation:

- No vegetation (not presented with equipment)
- Trees along the right edge of the corridor
- Trees along the left edge of the corridor
- Trees along both edges of the corridor
- Trees along the right edge of the corridor and in the median
- Light vegetation on both edges of the corridor

Equipment:

- No equipment
- Three pieces of construction equipment (Configuration A, Figure 3-7)
- Three pieces of construction equipment (Configuration B, Figure 3-8)

As with the previous experiments, in all work zones with drums, a 120 ft. spacing was utilized upstream of the diverge.

An image was generated for each combination of the listed features. These combinations generated 320 separate static images. Three replications of each image were produced, resulting in a total of 960 images that were shown to each participant. The images were presented to each participant with two rest periods, which occurred after each set of 320 images. Images within the set of 320 images were provided in a different random order for each participant. Participant rest periods were of variable duration and the maximum duration of the study was one hour. Most participants completed the experiment within 45 minutes.

Figure 3-7 Illustration of Experiment 3 Equipment, Configuration A

Figure 3-8 Illustration of Experiment 3 Equipment, Configuration B

3.5 Data Processing

The data collected from each participant were (1) the x, y coordinates of their mouse click locations within the various images and (2) the time from the instant the image was displayed to the time of the mouse click. Each image was divided into zones for classifying each participant's responses based on the location they clicked on the screen. This allowed the researchers to assess the accuracy with which each participant was able to identify the ramp condition (open/closed) and the ramp location (for the ramp open condition). Participant responses were classified as Ramp Closed, Exit Open, Work Zone, Don't Know, and Indeterminate, as described below. Figure 3-9 and Figure 3-10 illustrate an overlay of the zoning system on a rendered image for Experiment 1 and Experiments 2 and 3, respectively.

- ***Ramp Closed.*** The response recorded if the participant clicked on the zone located in the bottom left of the screen. On all images an "Exit Closed" text box was shown in this area.
- ***Exit Open.*** The response registered if the participant clicked on the ramp diverge location. This response indicates that the participant interpreted the ramp as open and correctly identified the diverge location. This zone is defined as an area bounded by (1) a line two-thirds of the distance from the initial cursor position to the ramp opening centroid; 2) a line parallel to the horizon, including a 50-pixel buffer; (3) lines drawn from the initial cursor position to the outside edges of the ramp opening; and (4) lines drawn from the visible portions of the channelizing devices used to delineate the ramp opening.
- ***Work Zone.*** This zone included the construction zone and the adjacent area above the horizon, to the right of the exit. This participant response indicated the participant interpreted the ramp as open; however, they incorrectly identified the diverge location as being in the construction area.
- ***Don't Know.*** In Experiments 2 and 3, a zone labeled "Don't Know," as indicated by the white "Don't Know" button in Figure 3-10, was included in the upper left section of the screen to allow the participant to indicate they were unable to determine the status or location of the diverge.
- ***Indeterminate.*** The remaining areas in the image were zoned Indeterminate. If the participant's response was recorded in these areas, it impossible to know if the participant intended to indicate the ramp diverge as open or closed.

To operationalize these definitions and to associate particular participant responses with a zone, the data were imported into "R" statistical software. The "R" software package is an open source implementation of the "S" statistical programming language originally developed by the Bell Telephone Laboratories in the 1970s. A set of R scripts using the "point.in.polygon" command was developed to first overlay x, y coordinates of each participant's responses onto the still

images, and then to process the graphical data into spreadsheets containing binary information indicating the zone in which each response was located.

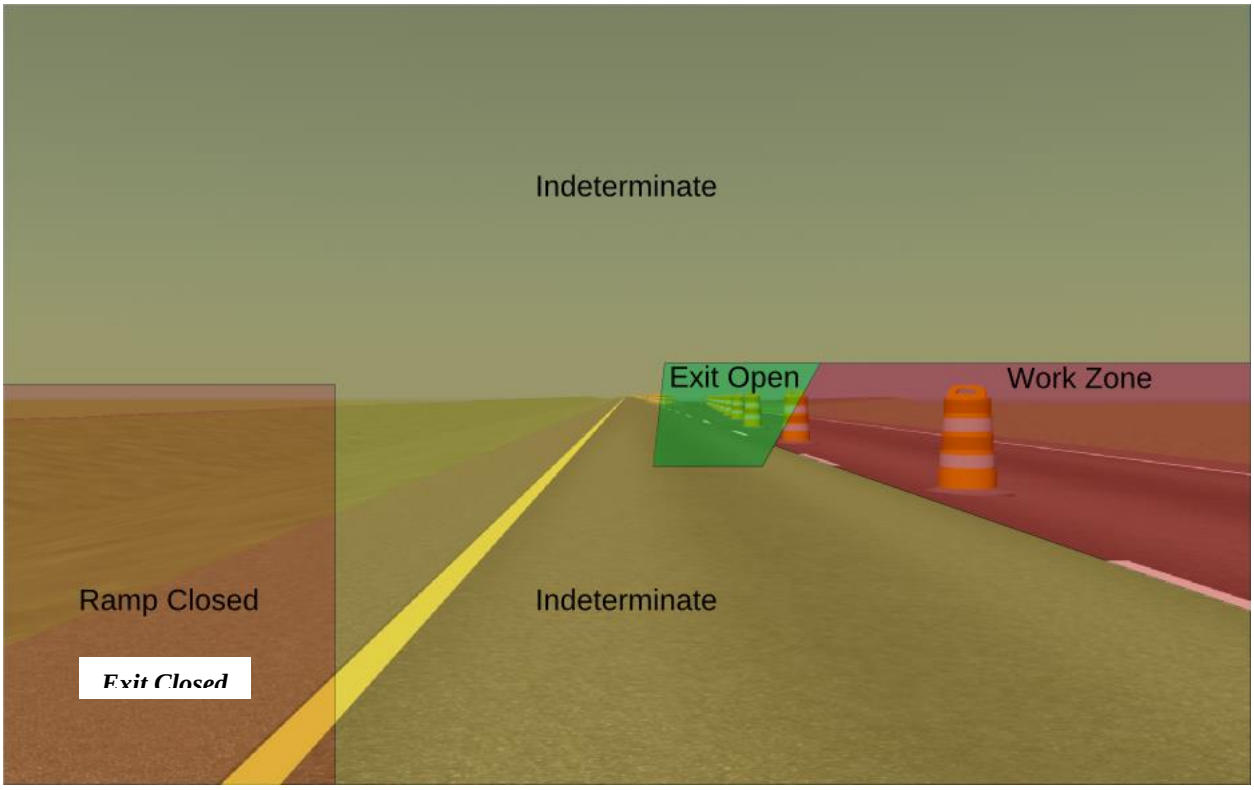

Figure 3-9 Zoning System for Classifying Responses in Experiment 1

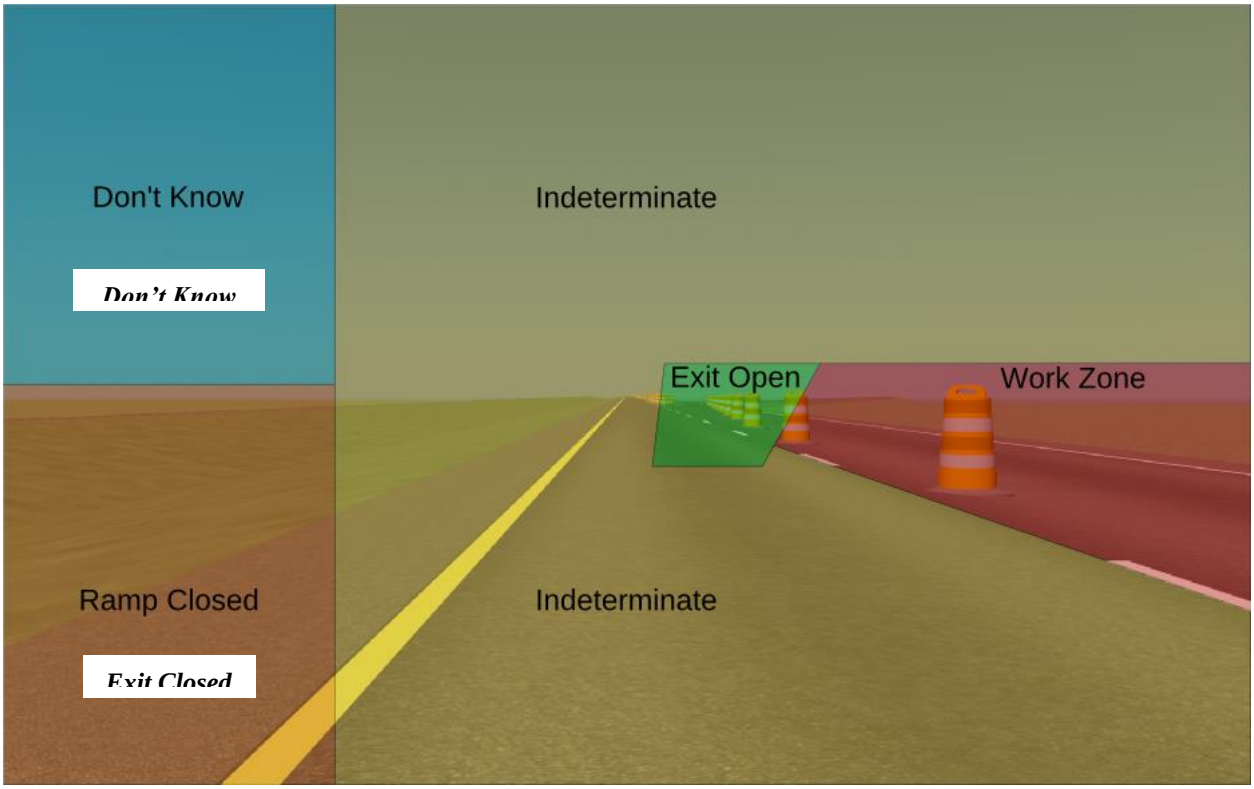

Figure 3-10 Zoning System for Classifying Responses in Experiments 2 and 3

3.6 Data Quality

As a quality assurance check on the software assignment process, researchers performed an image-by-image visual inspection of the responses for each participant. This process revealed two issues that required corrections.

The first issue was associated with the resolution of the computer monitors. Because of equipment changes during the study period, the resolution of the monitors was altered. Unfortunately, the software used to present the images to the participants and record their responses (Inquisit®) did not automatically adjust to that change. This resolution difference resulted in a proportional shift in the reported results. To correct for this shift, the impacted data were transformed from the resolution used by the participant to a standard resolution of 1680 × 1050 pixels for purposes of analysis.

The second issue was associated with the performance of several specific participants. Across all three experiments, six participants made a considerable number of erroneous responses (probably due to a lack of understanding of the experimental instructions), with two of them making very few actual responses (i.e., most images timed out). One additional participant did not finish the experiment. To ensure the data analysis was not biased due to abnormal participant errors,

responses from participants whose overall percentage of correct responses was lower than 25% were removed from further analysis.

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4 Results and Analysis

For each of the experiments, the results from the individual participants for all replicates of a particular combination of conditions were combined. From this compilation, the research team produced three types of descriptive results related to the speed and accuracy that the participant could identify the ramp position and location. In turn, the individual results could also be further aggregated to produce outcomes for the entire experimental cohort. These results were as follows:

***Percent Correct*:** A correct response for an open ramp is when a participant (1) identified the ramp as open and (2) correctly identified the ramp location. For a closed ramp, the response is correct if the participant correctly identified the ramp as closed. For example, for an open ramp a response is considered correct when the participant's click is within the zone indicated by "Exit Open" in Figure 3-9 for Experiment 1 or Figure 3-10 for Experiments 2 and 3. Thus, for an open ramp, "80% correct" indicates that 20% of a participant's responses were either clicks outside of this zone, or non-response due to time-out. Likewise, for a closed ramp 80% correct indicates that 20% of a participant's responses were clicks outside of the "Ramp Closed" zone in Figure 3-9 for Experiment 1 or Figure 3-10 for Experiments 2 and 3, or non-response due to time-out.

Error Analysis: Two types of errors are analyzed. The first, referred to as an *identification error*, occurs when a participant incorrectly identifies the ramp condition (i.e., as open when closed or as closed when open). The second type of error is referred to as a *diverge location error*. This latter error can arise in two ways. For an open ramp, a diverge location error occurs when the participant incorrectly identifies the location of the diverge as being within the work zone. In the case of a closed ramp, a diverge location error occurs when the participant incorrectly identifies the ramp as open and indicates a diverge location in the active work zone and not at the intended diverge point.

Latency: Latency is the measure of the time between when the image is displayed and a click response is recorded. Correct response latencies measure the time to react, process, and perform an appropriate action regarding the scene.

4.1 Experiment 1: Existing Channelizing Devices

Experiment 1 focused on examining human performance resulting from existing channelizing devices and configurations at varying times-to-exit and geometries. Data were collected for 41 participants, two of whom were excluded for excessive non-responses (i.e., fewer than 25% of responses were outside the Indeterminate Zone). The remaining 39 participants were included in the subsequent analyses.

4.1.1 Percent Correct

The overall percent correct across all responses was 82.7%. The No Work alternative averaged 73.5% for correct responses. Consistent with earlier studies, the PCBs resulted in the highest overall percent correct, averaging 91.5 % across participants. The second highest overall correct response rates, at 82.8% correct, were for aligned Drums spaced both at 10 ft. and 40 ft. apart at the diverge. The slightly misaligned Drum alternative (40 ft. ± 2 ft.) had a slightly lower overall correct response rate at 78.4% correct. While overall correct rates (average correct over all time-to-exit, geometry, and ramp open/closed conditions) for each delineation device tended to differ by a small percentage, it will be seen that correct rates for certain conditions (e.g., higher time-to-exit locations) could differ dramatically.

To identify statistically significant differences in percent correct across channelizing device alternatives, an analysis of variance (ANOVA) was performed. Data were grouped by geometry, ramp setup, and time-to-exit distance combinations. For each combination the effects (i.e. percent correct) resulting from the type of delineation device selected were analyzed using one-way ANOVA with participant ID as a blocking variable. Because the percent correct statistic conforms to a binomial distribution and violates the assumption of normality required by ANOVA, an arcsine transformation was performed. Where significant ($p < 0.05$) differences between treatments existed for a geometry/ramp-setup/time-to-exit combination (i.e., at least one delineation device could be identified as having a correct response rate that was statistically different from the others), differences between each delineation type were analyzed through the Tukey method of pairwise comparison.

Table 4-1 and Table 4-2 provide the percent correct for straight and curved geometry, respectively. Table 4-3 and Table 4-4 give the percent correct for each delineation alternative for open and closed conditions, at each time-to-exit, for the straight and curved freeway geometry, respectively. These latter two tables give results as differences in percent correct results (e.g., if treatment A was 30% correct and treatment B was 50% correct, the table value for B–A would be 20%).

Table 4-1 Percent Correct for Experiment 1 – Straight Geometry

Condition	Time-to-Exit	10 ft. Drums	40 ft. Drums	40 ± 2 ft. Drums	PCB
Open	5	75.13%	76.92%	34.10%	76.92%
	4	78.72%	79.74%	45.38%	83.33%
	3	87.18%	86.67%	77.44%	87.95%
	2	92.05%	88.97%	88.72%	91.79%
	1	93.33%	93.59%	93.33%	94.36%
Closed	5	62.31%	63.85%	60.77%	97.69%
	4	66.15%	67.44%	70.77%	96.15%
	3	65.90%	63.85%	70.26%	96.41%
	2	61.79%	64.10%	69.74%	95.90%
	1	92.82%	91.54%	74.36%	96.15%

Table 4-2 Percent Correct for Experiment 1 – Curved Geometry

Condition	Time-to-Exit	10 ft. Drums	40 ft. Drums	40 ± 2 ft. Drums	PCB
Open	5	84.62%	84.87%	85.13%	81.03%
	4	86.92%	87.69%	87.95%	85.13%
	3	90.26%	86.67%	86.41%	88.97%
	2	88.97%	89.23%	89.23%	84.10%
	1	91.28%	88.21%	91.28%	90.51%
Closed	5	80.00%	81.28%	85.64%	96.92%
	4	81.28%	84.87%	84.10%	95.13%
	3	84.87%	85.13%	87.69%	96.15%
	2	95.64%	94.87%	90.26%	96.67%
	1	96.92%	96.41%	95.13%	97.69%

For the straight geometry when the ramp was open, 40 ft. ± 2 ft. Drums (misaligned drums) resulted in a statistically significant and considerably lower percent correct than the other three channelizing devices at 5, 4, and 3 seconds away from the diverge. Differences in percent correct between the PCB, 40 ft. Drums, and 10 ft. Drums at 5, 4, and 3 seconds are on the order of a few percent and were not shown to be statistically significant. There were no statistically significant differences in percent correct among channelizing devices at 2 seconds and 1 second away. Thus, for future experiments only one of these conditions would be used.

When the ramp was closed in the straight geometry, PCB resulted in a greater percent correct than the other three channelizing device alternatives at 5, 4, 3, and 2 seconds away. The three alternative drum setups did not show any meaningful differences in percent correct at these distances. At 1 second away from the diverge, 40 ft. ± 2 ft. Drums resulted in fewer percent correct than for the other alternatives.

Table 4-3 Effects Table of Percent Correct for Experiment 1 – Straight Geometry

Condition	Time-to-Exit	PCB – 40 ± 2 ft. Drums	PCB – 40 ft. Drums	PCB – 10 ft. Drums	40 ft. Drums – 40 ± 2 ft. Drums	10 ft. Drums – 40 ± 2 ft. Drums	40 ft. Drums – 10 ft. Drums
Open	5	42.82% *0.0000000**	0.00% *0.9989280*	1.79% *0.9995150*	42.82% *0.0000000**	41.03% *0.0000000**	1.79% *0.9891400*
	4	37.95% *0.0000000*	3.59% *0.9359780*	4.62% *0.9766890*	34.36% *0.0000000**	33.33% *0.0000000**	1.03% *0.9996920*
	3	10.51% *0.007095**	1.28% *0.9999680*	0.77% *0.9982590*	9.23% *0.010083**	9.74% *0.018066**	–0.51% *0.9997120*
	2	No Significant Differences					
	1	No Significant Differences					
Closed	5	36.92% *0.0000000**	33.85% *0.0000000**	35.38% *0.0000000**	3.08% *0.7895510*	1.54% *0.9943720*	1.54% *0.9056400*
	4	25.38% *0.0000000**	28.72% *0.0000000**	30.00% *0.0000000**	–3.33% *0.9074060*	–4.62% *0.6789720*	1.28% *0.9702220*
	3	26.15% *0.0000000**	32.56% *0.0000000**	30.51% *0.0000000**	–6.41% *0.4428730*	–4.36% *0.6451900*	–2.05% *0.9882030*
	2	26.15% *0.0000000**	31.79% *0.0000000**	34.10% *0.0000000**	–5.64% *0.6083090*	–7.95% *0.3046320*	2.31% *0.9552770*
	1	21.79% *0.0000000**	4.62% *0.3250980*	3.33% *0.8321070*	17.18% *0.0000490*	18.46% *0.000001**	–1.28% *0.8253530*

Table 4-4 Effects Table of Percent Correct for Experiment 1 – Curved Geometry

Condition	Time-to-Exit	PCB – 40 ± 2 ft. Drums	PCB – 40 ft. Drums	PCB – 10 ft. Drums	40 ft. Drums – 40 ± 2 ft. Drums	10 ft. Drums – 40 ± 2 ft. Drums	40 ft. Drums – 10 ft. Drums
Open	5	No Significant Differences					
	4	No Significant Differences					
	3	No Significant Differences					
	2	No Significant Differences					
	1	No Significant Differences					
Closed	5	11.28% *0.000664**	15.64% *0.000004**	16.92% *0.000001**	–4.36% *0.599941*	–5.64% *0.312328*	1.28% *0.961892*
	4	11.03% *0.003724**	10.26% *0.035300**	13.85% *0.000401**	0.77% *0.874823*	–2.82% *0.921016*	3.59% *0.509804*
	3	8.46% *0.012416**	11.03% *0.006309**	11.28% *0.005919**	–2.56% *0.9962050*	–2.82% *0.9950850*	0.26% *0.9999970*
	2	6.41% *0.005724**	1.79% *0.775298*	1.03% *0.996154*	4.62% *0.081301*	5.38% *0.01136**	–0.77% *0.883481*
	1	2.56%	1.28%	0.77%	1.28%	1.79%	–0.51%

		0.021091*	0.662277	0.497178	0.286426	0.428087	0.993646

In the curved geometry, no statistically significant differences in percent correct were found when the ramp was open. When the ramp was closed, from 3 to 5 seconds away from the diverge, PCB again showed greater percent correct than all the drum alternatives. At 2 seconds away from the diverge 40 ft. ± 2 ft. Drums continue to result in moderately worse performance, on the order of 4% to 7% decrease in correct responses relative to the other channelization alternatives. By 1 second away from the diverge, minimal differences (less than 3%) were found among all channelization approaches.

In summary, in Experiment 1, PCB resulted in the highest and most consistent rate of correct responses, followed by Drums at 40 ft. and 10 ft. with 40 ft. ± 2 spacing having high error rates under several conditions. With some exceptions the percent correct tended to be lower the farther away from the diverge. Finally, the straight alignment general proved more challenging for participants that the curved.

4.1.2 Types of Errors

This section summarizes the error analysis associated with the alternatives examined in Experiment 1.

Straight Geometry/Open Condition. As shown in Figure 4-1, in the straight geometry and open condition, errors increased as the time-to-exit increased across all channelization alternatives. PCB resulted in the best participant performance, having Indeterminate responses dominate the recorded errors and almost no Identification errors. For 40 ft. Drums, there were few errors at the 1, 2, and 3 second times-to-exit, with most incorrect responses being categorized as Indeterminate. At 4 and 5 seconds, error rates exceeded 20%, mostly due to Indeterminate responses but also due to an increase in both Identification errors (stating the work zone was closed when it was open) and Diverge Location errors (identifying the diverge location as in the construction area).

Drums 10 ft. apart had a similar pattern of participant error; however, a distinctly different pattern was observed for 40 ft. ± 2 ft. Drums. For those scenes with misaligned drums, Identification errors increased as the time-to-exit increased—from 0.51% at 1 second away from the diverge to 50% at 5 seconds away from the diverge. Thus, the primary error at larger distances is identifying the diverge as closed when it is open. Diverge Location errors also increased with distance, from zero at 1 second away to 6.92% at 5 seconds away from the diverge. At distances of 4 to 5 seconds from the diverge that alternative also began to see an increase in participant time-out conditions, a potential additional indication that the participants had difficulty in interpreting these scenes with 40 ft. ± 2 ft. Drums.

Straight Geometry/Closed Condition. In the straight geometry and closed condition, shown in Figure 4-2, the dominant error type across drum alternatives was the Diverge Location error. At 1 second from the diverge, 40 ft. ± 2 ft. Drums showed a Diverge Location error rate of 13.33% and an Identification error rate of 7.69%. At 2 to 5 seconds from the diverge, all drum alternatives showed high Diverge Location errors, ranging from 15.64% to 29.23%. Identification errors resulting from drum alternatives at 2 to 5 seconds away ranged from 2.31% to 7.95%. In contrast, portable concrete barriers resulted in very few Diverge Location or Identification errors across all distances. The highest PCB Diverge Location error rate was 0.51% at 4 seconds away from the diverge, and the greatest percent of Identification errors was 1.28% at 2 seconds.

Curved Geometry/Open Condition. Patterns of error rates were more difficult to extract from the curved geometry when the ramp was open as the errors were generally smaller than for the straight alignment. Figure 4-3 shows the error type distribution for the curved geometry when the ramp was open. At 1 second away from the diverge, all channelizing devices resulted in no Diverge Location errors. Among all the alternatives of channelizing devices, 40 ft. ± 2 ft. Drums resulted in the greatest percent of Identification errors, at 1.54%. At 2 seconds away from the diverge, drum alternatives began to result in Diverge Location errors, although all were below 4% with PCB at 0% work zone errors. Identification errors also showed a similar trend for all channelizing devices. At 3, 4, and 5 seconds away, PCB continued to show zero Diverge Location errors and very low Identification errors, while the drum alternatives showed increasingly greater Diverge Location and Identification errors. Interestingly, three participants consistently made Diverge Location errors when the drum alternatives were used, but not for the portable concrete barrier alternative, suggesting that the gaps between drums may have a more pronounced effect on some individuals than for others. Even though the percent of errors was low, one can still observe the trend in which Diverge Location and Identification errors increased for drum alternatives as time-to-exit increased.

Curved Geometry/Closed Condition. In the curved geometry and closed condition, shown in Figure 4-4, the dominant error type across drum alternatives was, as in the straight geometry, the Diverge Location error. However, this trend was not as pronounced as in the straight geometry. Diverge Location errors began to rise at 3 seconds from the diverge, and at 3 to 5 seconds from the diverge, all drum alternatives showed high Diverge Location errors, ranging from 5.38% to 12.82%. Identification errors across all alternatives and distances to the exit were below 3%. As in the straight geometry, portable concrete barriers resulted in very few Diverge Location or Identification errors across all distances. The highest PCB Identification error rate was 1.54% at 4 seconds away from the diverge, and there were no Diverge Location errors.

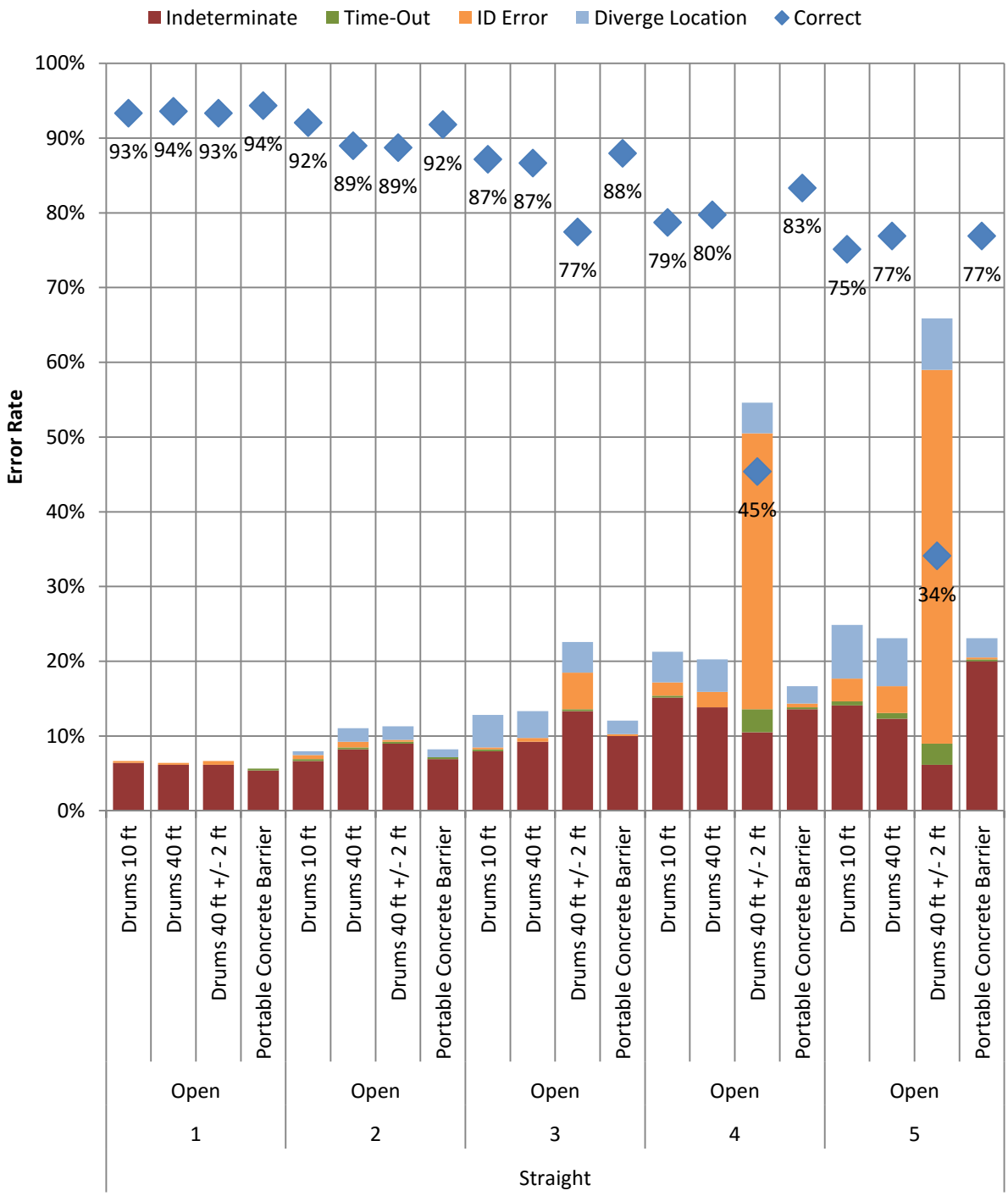

Figure 4-1 Experiment 1 – Percent Errors in the Straight Geometry and Open Condition (Numbers below the blue diamonds indicate the percent of correct responses.)

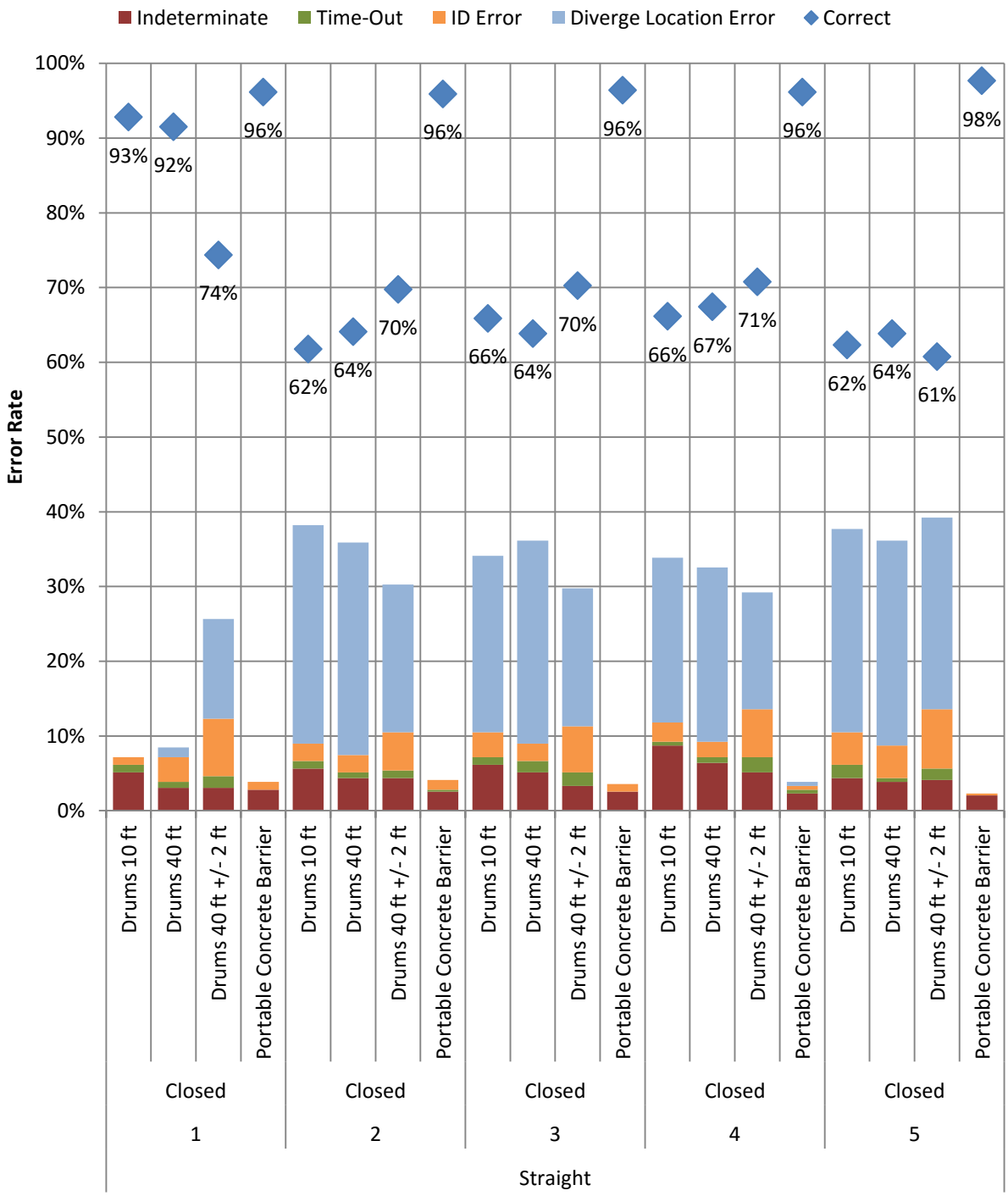

Figure 4-2 Experiment 1 – Percent Errors for the Straight Geometry and Closed Condition (Numbers below the blue diamonds indicate the percent of correct responses.)

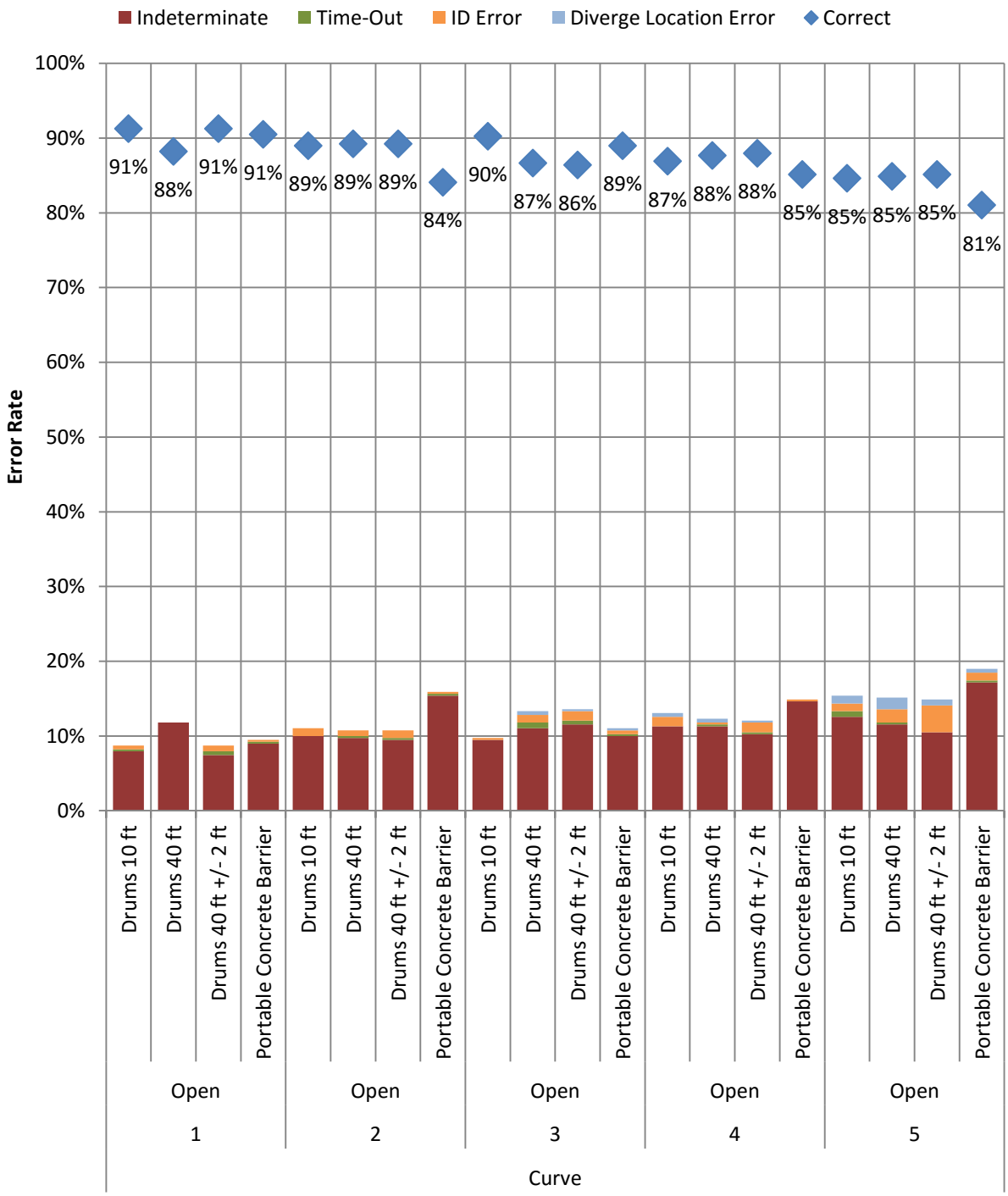

Figure 4-3 Experiment 1 – Percent Errors for the Curved Geometry and Open Condition (Numbers below the blue diamonds indicate the percent of correct responses.)

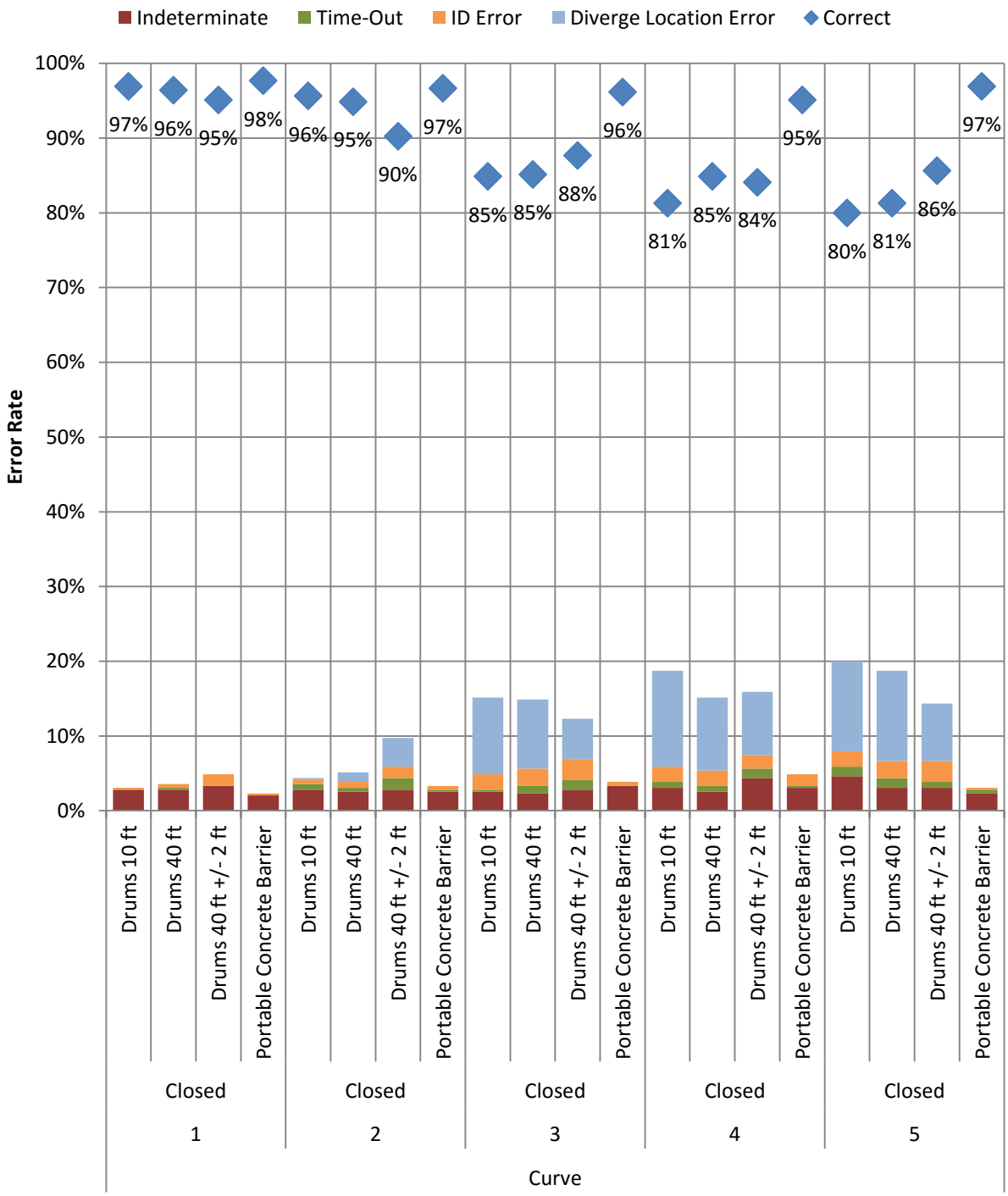

Figure 4-4 Experiment 1 – Percent Errors for the Curved Geometry and Closed Condition (Numbers below the blue diamonds indicate the percent of correct responses.)

4.1.3 Correct Response Latency

Correct response latencies are used to further assess human performance resulting from the use of different channelizing devices. The correct response latency allows for an exploration of how quickly a participant was able to make a correct response, potentially providing an additional indication of the perceived visual complexity of the channelization. For each treatment (i.e., image), the median latency across trials is taken to represent the correct response latency for the given participant under the given treatment. If a participant did not make any correct responses under one treatment, the latency for that particular participant and treatment is null, and it is excluded from further analysis. The central tendency of correct response latency is assessed by taking an arithmetic mean of the participant-specific median latencies across participants. The level of between-participant variation for the correct response latency is represented by taking the 25th and 75th percentiles of median latencies across participants. Figure 4-5 summarizes the results for Experiment 1.

The latencies illustrated in Figure 4-5 indicate how quickly, on average, participants were able to make a correct response. A few general observations can be made from the figure. First, the "Closed" conditions uniformly show longer average correct response latencies compared to the "Open" conditions. Second, the "Curved" geometry generally shows shorter latencies than the "Straight" geometry. Third, latency generally increases at further time-to-exits. Lastly, and most importantly, a few trends emerge regarding channelizing devices:

- The No Work and PCB alternatives almost always show the shortest latencies This trend is especially discernible for the more difficult scenes, i.e., for further times-to-exit, under Straight geometry, and when the ramp is closed.
- The 40 ft. ± 2 ft. Drums alternative shows the longest latencies. This trend holds true for all Straight geometry scenes.
- The 10 ft. Drums and 40 ft. Drums alternatives result in similar latencies

In addition to average latency, Figure 4-5 also shows the 25th and 75th percentiles of the median latency by participant, depicted by the bars in the chart. The length of the bar is an indication of the magnitude of the variability between participants for the correct response latency. That is, the longer the bar, the more varied the correct response latencies were across participants. Intuitively, a "better" channelizing device would feature shorter bars (in addition to having short latencies), indicating more similar responses across participants. Similar to the observations above regarding average latencies, the between-participant variability suggests the following characteristics:

- Between participant variability of correct response latency increases with time-to-exit, especially under Straight conditions.

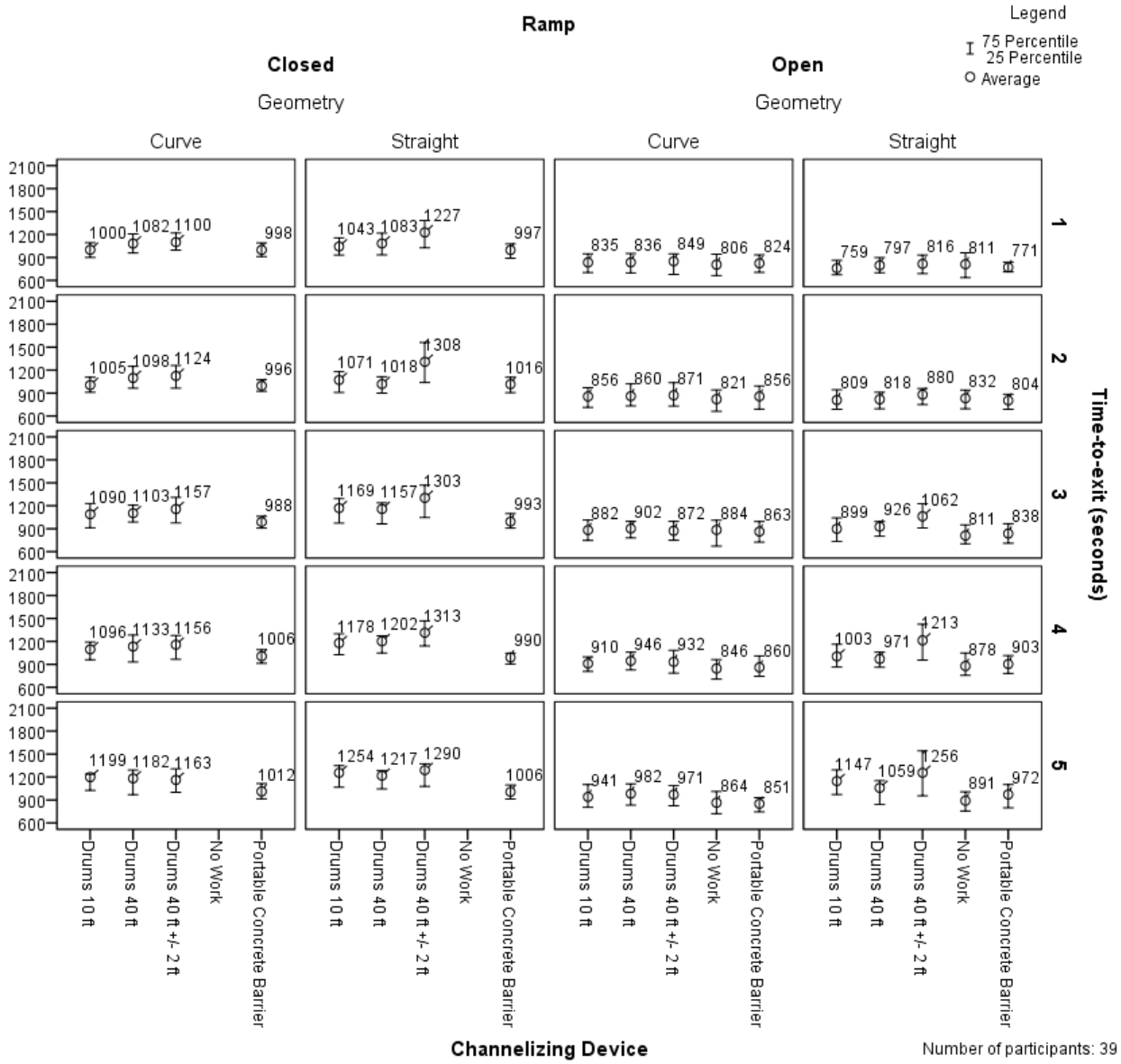

Figure 4-5 Experiment 1 – Correct Response Latency in Milliseconds by Channelizing Device

- The No Work and PCB alternatives show the lowest between-participant variability in most scenarios.
- The 40 ft. ± 2 ft. Drums scenario shows the highest between-participant variability under most conditions.

4.1.4 Discussion

Experiment 1 specifically evaluated existing work zone channelizing devices, all of which drivers likely would have encountered in their driving experiences. Sections 4.1.1 to 4.1.3 compared three key aspects of the performances of the channelizing devices: correct response rates, types of errors, and correct response latency. Figure 4-6 is a radar chart that provides a comprehensive comparison of the four channelizing devices in four measures, namely, percent correct, identification errors, diverge location errors, and correct response latency aggregated across geometry and ramp condition (open versus closed). The radar chart has four spokes or radii, one for each variable of interest. Each spoke is scaled from –1.0 to 1.0. For each spoke, 0.0 indicates the alternative with the least desirable performance for the measure represented and 1.0 denotes the best alternative. For example, based on percent correct, 40 ft. ± 2 ft. Drums had the lowest value while PCB had the highest. For the remaining alternatives the distance from zero represents for the relative difference between that alternative and the least desirable, scaled by the difference between the least desirable and best alternatives. This graph allows for a quick simultaneous comparison of channeling device alternatives across the various measures.

It is readily seen in this comparison that delineation devices (e.g., PCBs) with high linearity and continuity dominate in all performance measures tested. As illustrated in Figure 4-6, PCB ranked consistently as the best channelizing device for all four measures. The 40 ft. ± 2 ft. Drums alternative, which has the lowest linearity and continuity, correspondingly has the lowest performance. The 40 ft. ± 2 ft. Drums alternative ranked the worst for percent correct, identification errors, and correct response latency. The 10 ft. Drums and 40 ft. Drums alternatives were effectively the same in all measures, generally falling between PCBs and 40 ft. ± 2 ft. Drums.

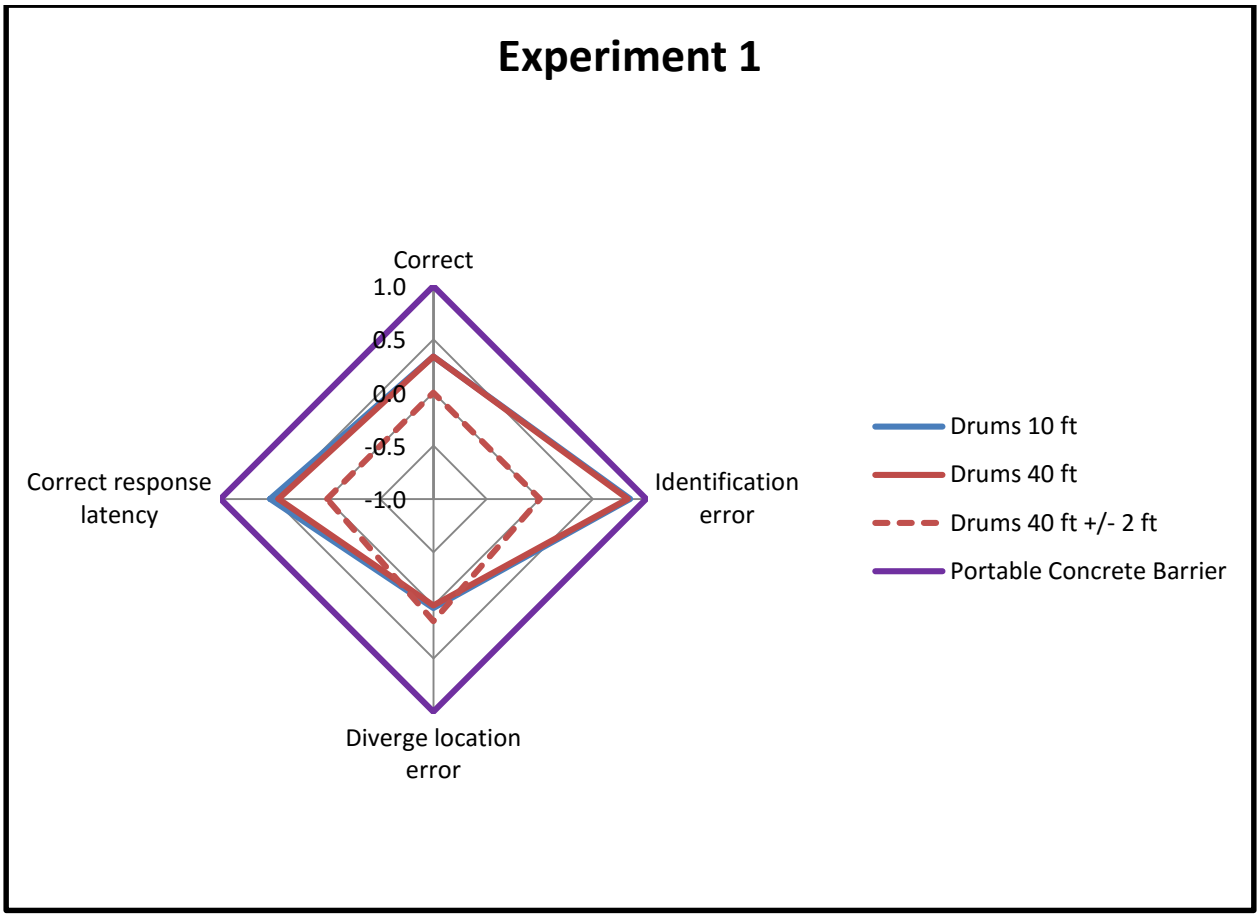

Figure 4-6 Comprehensive Comparison of Channelizing Devices in Experiment 1

4.2 Experiment 2: Novel Channelizing Device

Based on the results of Experiment 1, the research team determined that the linearity and continuity of the discrete devices (delineators) used for channelization were critical elements to achieving high accuracy in identification of the ramp diverge. These observations were the principal influence for the development of the Linear Channelizing Device described in Chapter 3. Experiment 2 added this Linear Channelizing Device to the spectrum of channelizing devices. To ensure the results were not a product of a specific drum placement configuration, this second experiment provided additional random placement combinations scenarios to the 40 ft. ± 2 ft. Drums alternatives used in Experiment 1.

For this experiment, student participants from Morehead State University were recruited rather than students from Georgia Tech. Among the 51 original participants at Morehead State, data from 4 participants were excluded from analysis according to the quality control process described in Section 3.6, resulting in 47 participants in the final dataset.

In addition to the inclusion of LCD and adaptations to the misaligned drums (± 2 ft.) alternatives, several other modifications to the Experiment 1 protocol were made in Experiment 2. Based on the limited information provided by the curved geometry, only the straight roadway geometry was used in the analysis of Experiment 2 data. Also, two random misalignment options for the 10 ft. ± 2 ft. alternative were included. Finally, clear trends observed in time-to-exit distances allowed for a reduction in distances included in Experiment 2, to 1, 3, and 5 seconds from the diverge point.

4.2.1 Percent Correct

The overall percent correct for Experiment 2 was 67.7%. The No Work alternative, used for control purposes, resulted in an average of 69.7% correct. As with Experiment 1, PCBs resulted in the highest percent correct, averaging 85.1%. The second highest percent correct resulted from the new LCD treatment with all pylons in place, at 80.8%, with LCD missing 10% of the pylons slightly lower, averaging 78.6%. Also consistent with Experiment 1, the 10 ft. and 40 ft. Drums (properly aligned) gave very similar results, averaging 67.4% and 68.3% correct, respectively. The two misaligned Drum options were also very similar (61.6% and 59.7% correct) but notably lower than the properly aligned options. As with Experiment 1, it will be seen that correct rates across delineation types for certain conditions will differ dramatically more than the overall average values.

For the straight geometry used in Experiment 2, Table 4-5 lists the percent correct for each alternative at each distance. Table 4-6 compares the percent differences in correct responses resulting from the ANOVA and Tukey procedures.

When the ramp was open, the ANOVA and the Tukey procedure identified significant percent correct differences resulting from the different channelizing devices at travel time distances of 5 and 3 seconds away from the diverge. At 5 seconds away from the diverge, statistical significance in performance was found between every pair of channelizing devices except between LCD and PCB. From the greatest percent correct to the lowest, the channelizing devices were ranked as: LCD and PCB, LCD missing 10% of pylons, 10 ft. Drums, 40 ft. Drums, 40 ft. ± 2 ft. Drums, and 10 ft. ± 2 ft. Drums. Percent differences between devices offering the most linear scene (i.e., PCB and LCD) and those with the most potentially disjointed scene (i.e., 10 ft. ± 2 ft. and 40 ft. ± 2 ft.) typically approached or exceeded 50%. At 3 seconds away from the diverge, PCB, LCD, LCD missing 10% of pylons, 40 ft. Drums and 10 ft. Drums showed no significant difference in the percent correct. Collectively, the aforementioned five channelizing devices consistently had 20% to 25% higher correct rates than the 40 ft. ± 2 ft. Drums and the 10 ft. ± 2 ft. Drums. No significant difference was found between 40 ft. ± 2 ft. Drums and 10 ft. ± 2 ft. Drums. At 1 second away from the diverge, no statistically significant difference was found between any channelizing devices regarding percent correct.

When the ramp was closed, significant differences in percent correct were found at all times-to-exit, although the magnitude of the differences tended to be lower than in the open condition. At 5 seconds away from the ramp diverge, PCB, LCD, and LCD missing 10% of pylons resulted in statistically significant greater percent correct than all four of the drum channelizing device alternatives. At 3 seconds away from the diverge, the PCB, LCD, and LCD missing 10% of pylons resulted in statistically significant greater percent correct than 40 ft. Drums, 10 ft. Drums, and 10 ft. ± 2 ft. Drums. Similarly, 40 ft. Drums, 10 ft. Drums, and 10 ft. ± 2 ft. Drums had statistically significant greater percent correct than 40 ft. ± 2 ft. Drums. At 1 second away from the diverge, all channelizing devices other than 40 ft. ± 2 ft. Drums showed no significantly different percent correct between alternatives. The 40 ft. ± 2 ft. Drums alternative was shown to result in statistically significant less percent correct compared with all other channelizing devices.

Table 4-5 Percent Correct for Experiment 2

Condition	Time-to-Exit	10 ft. Drums	10 ± 2 ft. Drums	40 ft. Drums	40 ± 2 ft. Drums	LCD	LCD–10%	PCB
Open	5	36.42%	16.05%	41.36%	25.51%	62.35%	58.33%	72.22%
	3	87.96%	65.02%	87.04%	66.77%	88.89%	90.12%	89.51%
	1	96.30%	95.68%	96.91%	94.86%	96.60%	95.99%	96.30%
Closed	5	53.40%	48.77%	52.16%	55.56%	78.40%	75.00%	83.64%
	3	56.17%	60.49%	54.32%	50.00%	78.70%	75.31%	83.33%
	1	69.75%	78.91%	72.22%	58.54%	77.16%	75.31%	83.33%

Table 4-6 Effects Table of Percent Correct for Experiment 2

Condition	Time-to-Exit	LCD–10% – 40 ± 2 ft. Drums	LCD–10% – 40 ft. Drums	LCD–10% – 10 ± 2 ft. Drums	LCD–10% – 10 ft. Drums	10 ft. Drums –40 ± 2 ft. Drums	10 ft. Drums –40 ft. Drums	10 ft. Drums – 10 ± 2 ft. Drums	40 ft. Drums – 40 ± 2 ft. Drums	40 ft. Drums – 10 ± 2 ft. Drums	40 ± 2 ft. Drums – 10 ± 2 ft. Drums
Open	5	31.09% *0.0000000**	16.67% *0.039856**	41.02% *0.0000000**	19.86% *0.00218**	11.23% *0.0000000**	–3.19% *0.990843*	21.16% *0.0000000**	14.42% *0.000427**	24.35% *0.0000000**	9.93% *0.004056**
	3	23.05% *0.0000000**	2.48% *0.999943*	25.53% *0.0000000**	2.13% *0.998003*	20.92% *0.0000000**	0.35% *0.999994*	23.40% *0.0000000**	20.57% *0.0000000**	23.05% *0.0000000**	2.48% *0.998726*
	1	No Significant Differences									
Closed	5	17.38% *0.000189**	19.86% *0.00015**	25.41% *0.0000000**	20.57% *0.000127**	–3.19% *0.923180*	–0.71% *1.000000*	4.85% *0.851683*	–2.48% *0.936187*	5.56% *0.830394*	8.04% *0.01216**
	3	24.47% *0.0000000**	20.57% *0.000008**	13.83% *0.002025**	19.86% *0.000007**	4.61% *0.986295*	0.71% *1.000000*	–6.03% *0.182811*	3.90% *0.981629*	–6.74% *0.201504*	–10.64% *0.000128**
	1	16.08% *0.00005**	3.19% *0.967915*	–4.02% *0.912538*	5.32% *0.822567*	10.76% *0.032786**	–2.13% *0.999502*	–9.34% *0.074806*	12.88% *0.005691**	–7.21% *0.253287*	–20.09% *0.0000000**

Condition	Time-to-Exit	PCB – 40 ± 2 ft. Drums	PCB – 40 ft. Drums	PCB – 10 ± 2 ft. Drums	PCB – 10 ft. Drums	PCB – LCD	PCB – LCD–10%	LCD – 40 ± 2 ft. Drums	LCD – 40 ft. Drums	LCD – 10 ± 2 ft. Drums	LCD – 10 ft. Drums	LCD – LCD–10%
Open	5	47.04% *0.0000000**	32.62% *0.0000000**	56.97% *0.0000000**	35.82% *0.0000000**	9.57% *0.401064*	15.96% *0.008686**	37.47% *0.0000000**	23.05% *0.000154**	47.40% *0.0000000**	26.24% *0.000003**	6.38% *0.825958*
	3	22.34% *0.0000000**	1.77% *0.999594*	24.82% *0.0000000**	1.42% *0.993786*	0.35% *0.999140*	–0.71% *1.000000*	21.99% *0.0000000**	1.42% *1.000000*	24.47% *0.0000000**	1.06% *0.999999*	–1.06% *0.999843*
	1	No Significant Differences										
Closed	5	25.53% *0.0000000**	28.01% *0.0000000**	33.57% *0.0000000**	28.72% *0.0000000**	4.61% *0.939917*	8.16% *0.466798*	20.92% *0.000001**	23.40% *0.000002**	28.96% *0.000002**	24.11% *0.0000000**	–3.55% *0.977564*
	3	32.27% *0.0000000**	28.37% *0.0000000**	21.63% *0.0000000**	27.66% *0.0000000**	4.61% *0.925490*	7.80% *0.489036*	27.66% *0.0000000**	23.76% *0.0000000**	17.02% *0.0000000**	23.05% *0.000032**	3.19% *0.986775*
	1	23.17% *0.0000000**	10.28% *0.119310*	3.07% *0.966537*	12.41% *0.037312*	6.03% *0.928771*	7.09% *0.614975*	17.14% *0.000001**	4.26% *0.724769*	–2.96% *0.438498*	6.38% *0.999643*	1.06% *0.996657*

4.2.2 Types of Errors

Figure 4-7 shows the error type distribution for the open ramp condition. At 1 second away from the diverge, errors are low across all channelizing devices. At 3 seconds, Diverge Location errors start to increase among the drum alternatives and LCD, ranging from 7.2% for 10 ft. ± 2 ft. Drums to 2.5% for LCD. Identification errors resulting from 10 ft. ± 2 ft. Drums and 40 ft. ± 2 ft. Drums increase to about 13%, while the Identification errors of all other channelizing devices remain low, at or below 2%. At 5 seconds, Diverge Location and Identification errors increase across all channelizing devices, but the rate of increase is much greater among the drum alternatives than among PCB, LCD, and LCD missing 10% of pylons. For 10 ft. ± 2 ft. Drums and 40 ft. ± 2 ft. Drums, every participant made at least two errors in identifying the open diverge point at 5 seconds away from the diverge. These results reinforce the Experiment 1 observation that a small amount of variation in drum placement can cause a significant increase in errors. Overall for the open condition, PCBs had the best performance of any alternative in the open condition. The Linear Channelizing Device also resulted in few errors in the ramp open condition.

Figure 4-8 shows the error type distribution when the ramp was closed. At 1 second travel time distance to the diverge, 40 ft. ± 2 ft. Drums, LCD, and LCD missing 10% of pylons had many Identification errors, at 20.1%, 14.8%, and 14.5%, respectively. The other channelizing devices all resulted in Identification errors of less than 5%. With regard to Diverge Location errors, properly aligned Drums at 40 ft. separation resulted in the greatest error rate at 5.25%. The second greatest percentage of Diverge Location errors, 1.1%, was observed with 40 ft. ± 2 ft. Drums. At 3 seconds away from the diverge, there were many Diverge Location errors for the drum alternatives, ranging from 15.6% to 28.7%. Drums at 10 ft. ± 2 ft., 40 ft. ± 2 ft. Drums, LCD, and LCD missing 10% of pylons resulted in greater Identification errors than the other channelizing devices. Similar trends were observed at 5 seconds away from the diverge, with the exception that the Identification errors for 10 ft. Drums and 40 ft. Drums were much greater at 5 seconds away than at 3 seconds away.

Similar to the trends under the open condition, when the ramp was closed, few errors were observed for all participants with PCB. LCD also resulted in good performance, although with greater Identification errors, most notably at 1 second away from the diverge. These results closely mirrored the results from Experiment 1 and demonstrate the effectiveness of a device designed following the Gestalt principles.

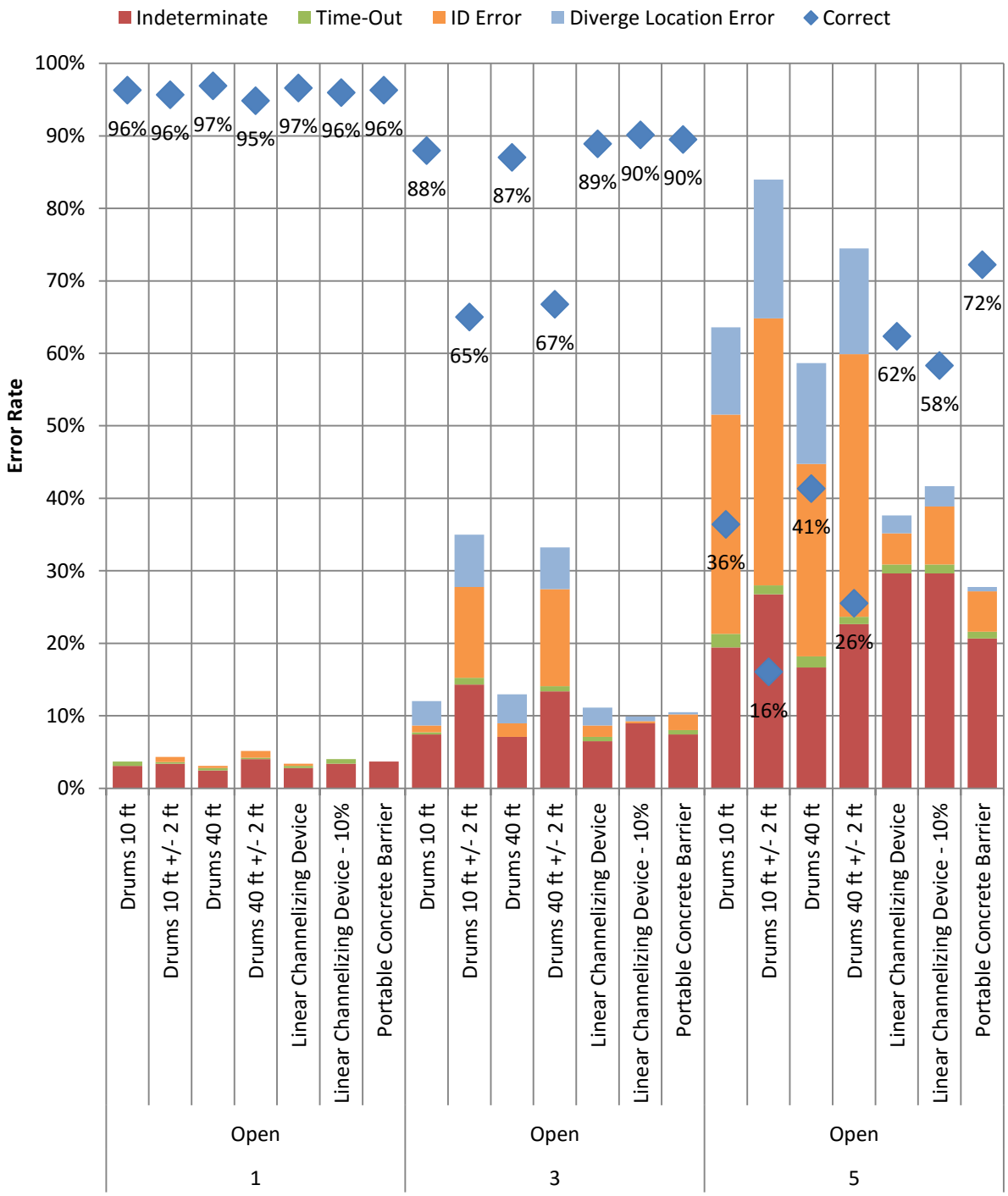

Figure 4-7 Experiment 2 – Percent Errors for the Straight Geometry and Open Condition (Numbers below the blue diamonds indicate the percent of correct responses.)

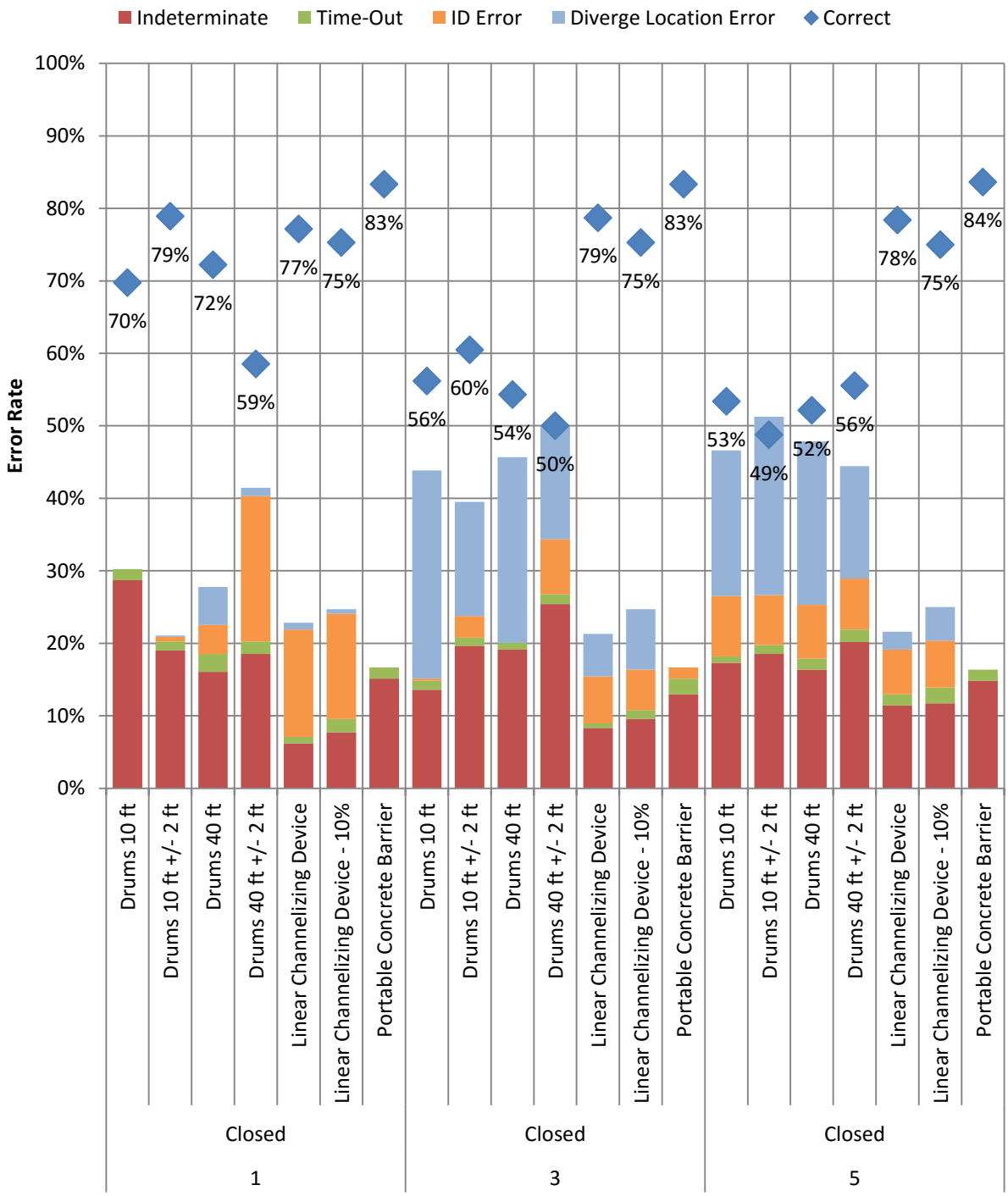

Figure 4-8 Experiment 2 – Percent Errors for the Straight Geometry and Closed Condition (Numbers below the blue diamonds indicate the percent of correct responses.)

4.2.3 Correct Response Latency

The trends in correct response latencies observed in Experiment 2 are comparable to those observed in Experiment 1. The key research question of concern in Experiment 2 was the performance resulting from LCD. Therefore, the analyses presented in this section focus on LCD. Correct response latencies for Experiment 2 are shown in Figure 4-9.

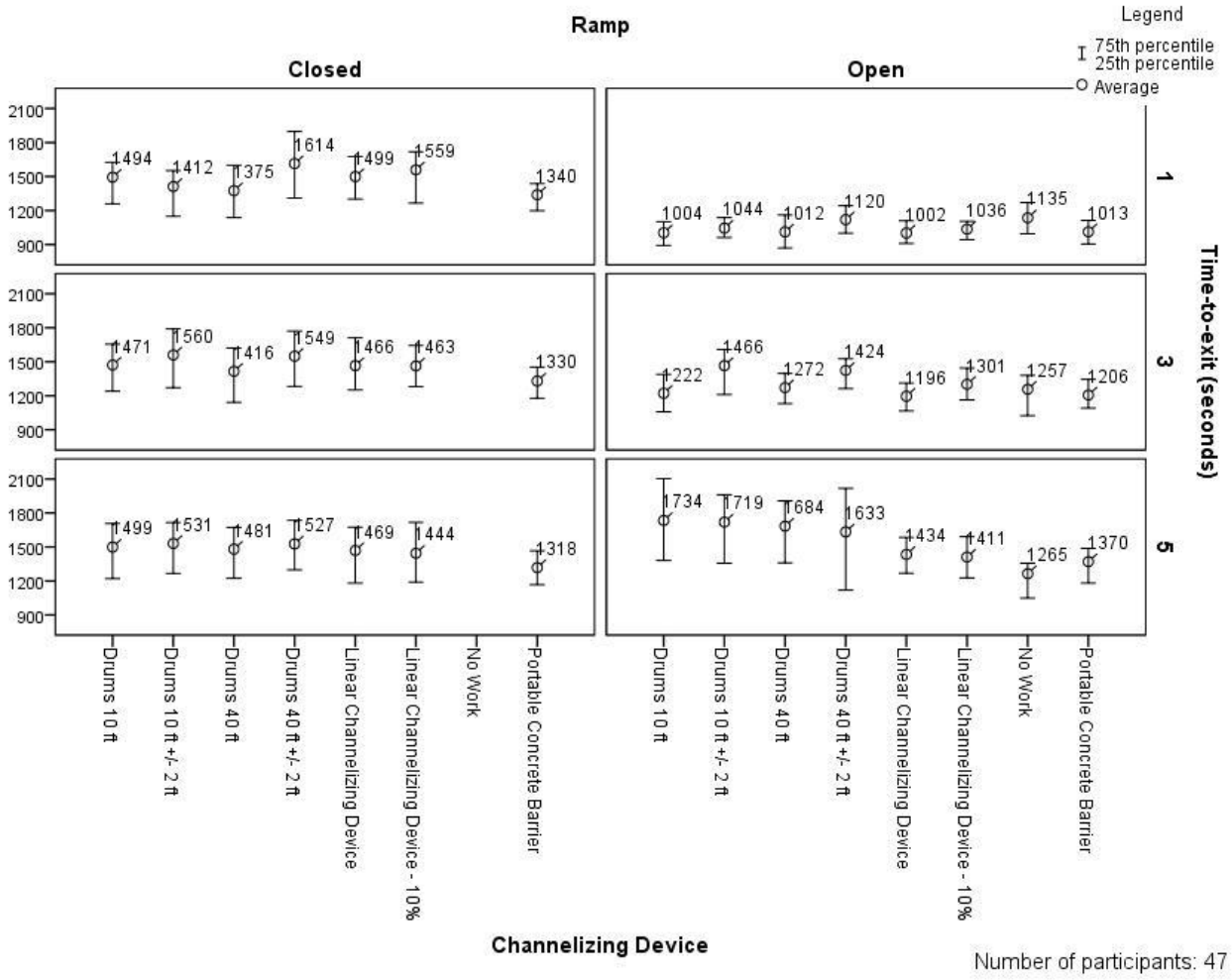

Figure 4-9 Experiment 2 – Correct Response Latency in Milliseconds by Channelizing Device

Similar to the results from Experiment 1, the average median latency by participant is generally shorter when the ramp is open than when the ramp is closed, indicating that it takes less time for a participant to interpret the scene when the ramp is open. The only exception to the trend is at 5 seconds travel time from the diverge, when all barriers involving drums show longer average latencies under the open condition compared to the closed condition. This likely results from increased difficulty in ramp detection at a significant distance from the exit where the diverge opening is delineated by drums.

LCDs also show different latency performance under closed versus open conditions. When the ramp is open, LCDs have comparable average latencies to PCBs and No Work, indicating similar ability in identifying the diverge opening for these three alternatives. However, when the ramp is closed LCD results in much longer average latencies than PCB, but similar performance to the drums alternatives.

The trends of the between-participant variability of correct response latencies (not shown) are similar to the trends of the average latencies. When the ramp is open, the performance of LCD is similar to that of PCB. When the ramp is closed, the performance of LCD is similar to that of drums.

4.2.4 Discussion

Experiment 2 introduced the Linear Channelizing Device, a new channelizing device based on the principles of closure and continuity exhibited by the portable concrete barrier. Figure 4-10 is a radar chart to visualize a comprehensive comparison among the channelizing devices tested in Experiment 2.

Similar to Experiment 1, PCB ranked as the best channelizing device in all four measures—percent correct, Identification errors, Diverge Location errors, and correct response latency. LCD was the second best channelizing device for all four measures. LCD missing 10% of pylons resulted in performance that was only slightly worse than LCD. Drums at 10 ft. and 40 ft. resulted in very similar performance, but 10 ft. ± 2 ft. Drums resulted in better performance than 40 ft. ± 2 ft. Drums in all measures except for work zone location errors. These results further demonstrate the effectiveness of traffic control devices that best follow the principles of closure and continuity.

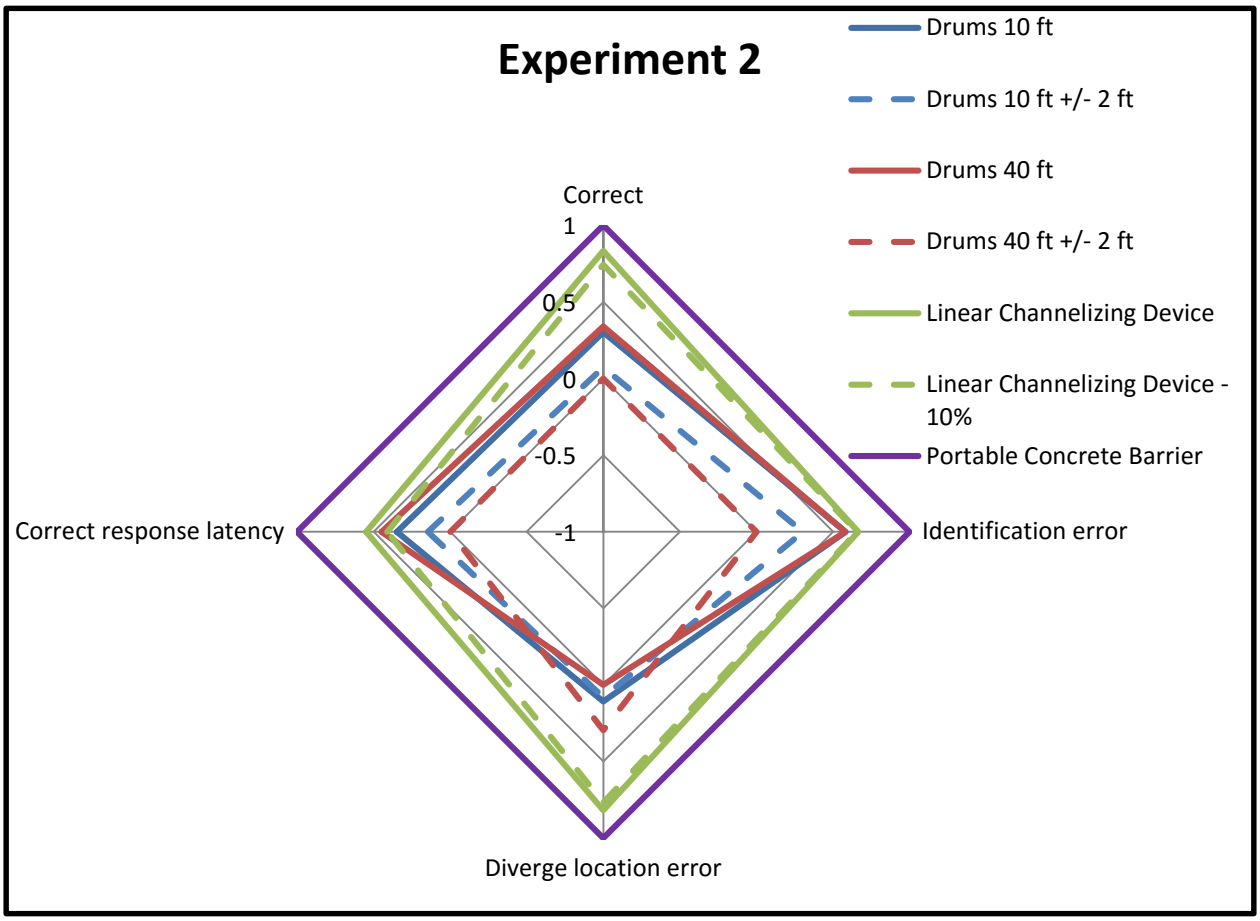

Figure 4-10 Comprehensive Comparison of Channelizing Devices in Experiment 2

4.3 Experiment 3: Varying Roadside Environment and Construction Equipment

Experiments 1 and 2 focused on sparse, straight-line horizon backgrounds to eliminate visual clutter beyond that imposed by the channelizing devices. Experiment 3 introduced varied backgrounds and construction equipment, exploring the transferability of the results from Experiment 3 to more realistic environments. Experiment 3 was conducted at both the Georgia Institute of Technology (18 Participants) and Morehead State University (20 participants).

4.3.1 Percent Correct

The overall percent correct across all responses in Experiment 3 was 90.5%. The PCB, LCD, and LCD missing 10% of pylons alternatives resulted in similar high correct percentage at 94.2%, 94.7%, and 94.4%, respectively. The 40 ft. Drums alternative resulted in an average percent correct of 90.3%. At 78.9%, 40 ft. ± 2 ft. Drums had the lowest percent correct. When comparing to Experiments 1 and 2, caution must be exercised as Experiment 3 does not include the 5 second travel distance to the diverge, which had the highest error rates. For instance, when considering only time-to-exit distances of 1 second and 3 seconds, the Experiment 2 straight geometry has corresponding percent correct rates of 88.74%, 85.99%, and 85.02% for PCB, LCD, and LCD missing 10%, respectively; the 40 ft. Drums and 40 ft. ± 2 ft. Drums alternatives each resulted in 78.81% and 68.85% correct responses. Thus, the trend is similar to the Experiment 3 results.

Table 4-7 gives the percent correct for each alternative at each distance, and summarizes the pair-wise comparisons of the percent correct for each channelizing device in Experiment 3.

When the ramp was open, there were no statistically significant differences in the percent correct among the five channelizing devices at 1 second travel time from the diverge. At 3 seconds from the diverge, the PCB, LCD, and LCD missing 10% of pylons alternatives also resulted in no significant difference in the percent correct. Collectively, the aforementioned three channelizing devices resulted in a statistically greater percent correct than 40 ft. Drums and 40 ft. ± 2 ft. Drums. Additionally, 40 ft. Drums resulted in significantly greater percent correct than 40 ft. ± 2 ft.

When the ramp was closed, statistical significance was found at both 1 second and 3 seconds from the diverge. At 1 second, PCB, LCD, LCD missing 10% of pylons, and 40 ft. Drums resulted in no significant difference in the percent correct. They all resulted in significantly greater percent correct than 40 ft. ± 2 ft Drums. At 3 seconds, the trends are the same as under the open condition.

Table 4-7 Percent Correct for Experiment 3

Condition	Time-to-Exit	40 ft. Drums	40 ± 2 ft. Drums	LCD	LCD−10%	PCB
Open	3	86.96%	77.63%	96.18%	95.76%	97.53%
	1	96.72%	81.96%	96.68%	95.14%	97.38%
Closed	3	86.96%	77.63%	96.18%	95.76%	97.53%
	1	96.72%	81.96%	96.68%	95.14%	97.38%

4.3.2 Types of Errors

Figure 4-11 shows the error type distribution for the open ramp condition in Experiment 3. When the ramp was open, the percentage of errors at 1 second travel time from the diverge for all channelizing devices was very small. At 3 seconds from the diverge, LCD and LCD missing 10% of pylons resulted in very few Identification errors, both less than 1%. PCB resulted in slightly greater Identification errors, at 4.5%. Alternatives of 40 ft. Drums and 40 ft. ± 2 ft. Drums resulted in the highest level of Identification errors at 8.5% and 24.3%, respectively. The percentage of Diverge Location errors were similar across channelizing devices, ranging from 2.3% for PCB to 4.4% for Drums with 40 ft. separation.

The error type distribution for the ramp closed condition in Experiment 3 is given in Figure 4-12. When the ramp was closed, error rates were generally small at both 1 second and 3 seconds time-to-exit, but they were more variable across channelizing devices than they were under the open ramp condition. At 1 second away from the diverge, 40 ft. ± 2 ft. Drums resulted in the greatest percent of Identification errors at 7.5%, compared with LCD missing 10% of pylons at 2.2%, the second greatest percent of Identification errors. At 3 seconds away from the diverge, 40 ft. ± 2 ft. Drums resulted in the greatest percent of Identification errors at 3.9%, while all other channelizing devices had negligible Identification errors. When considering Diverge Location errors, 40 ft. Drums resulted in the greatest percent of errors at 6.1%. At 4.4%, 40 ft. ± 2 ft. Drums resulted in the second most Diverge Location percent of errors.

This experiment also investigated the influence of different vegetation (Figure 4-13) and roadside equipment configurations (Figure 4-14) on performance. Generally, across all vegetation types, there were only slight differences in the resulting percentage of errors and error types. Similarly, for different equipment configurations the resulting differences in the percent of errors and error types was not significant. However, one notable exception was an increase in the percent of Diverge Location errors for alternatives without work zone equipment in the closed condition at 3 seconds. Further, over all the vegetation and equipment alternatives the LCD and PCB alternatives still demonstrate strong performance advantages over drum alternatives.

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Table 4-8 Effects Table of Percent Correct for Experiment 3

Condition	Time-to-Exit	PCB – 40 ± 2 ft. Drums	PCB – 40 ft. Drums	PCB – LCD	PCB – LCD–10%	LCD – 40 ± 2 ft. Drums	LCD – 40 ft. Drums	LCD – LCD–10%	LCD–10% – 40 ± 2 ft. Drums	LCD–10% – 40 ft. Drums	40 ft. Drums – 40 ± 2 ft. Drums
Open	3	24.69% *0.0000000**	4.98% *0.000027**	–3.78% *0.012852**	–4.36% *0.001223**	28.47% *0.0000000**	8.76% *0.0000000**	–0.58% *0.966700*	29.05% *0.0000000**	9.34% *0.0000000**	19.71% *0.0000000**
	1	1.04% *0.318949*	–0.73% *0.479758*	–0.50% *0.763077*	–0.42% *0.835044*	1.54% *0.017941**	–0.23% *0.991697*	0.08% *0.999923*	1.47% *0.027249**	–0.31% *0.977482*	1.77% *0.003921**
Closed	3	19.87% *0.0000000**	10.57% *0.0000000**	1.35% *0.480770*	1.77% *0.187472*	18.52% *0.0000000**	9.22% *0.0000000**	0.42% *0.981472*	18.09% *0.0000000**	8.80% *0.0000000**	9.30% *0.0000000**
	1	15.32% *0.0000000**	0.62% *0.898047*	0.66% *0.860591*	2.20% *0.008177**	14.66% *0.0000000**	–0.04% *0.999984*	1.54% *0.136286*	13.12% *0.0000000**	–1.58% *0.110359*	14.70% *0.0000000**

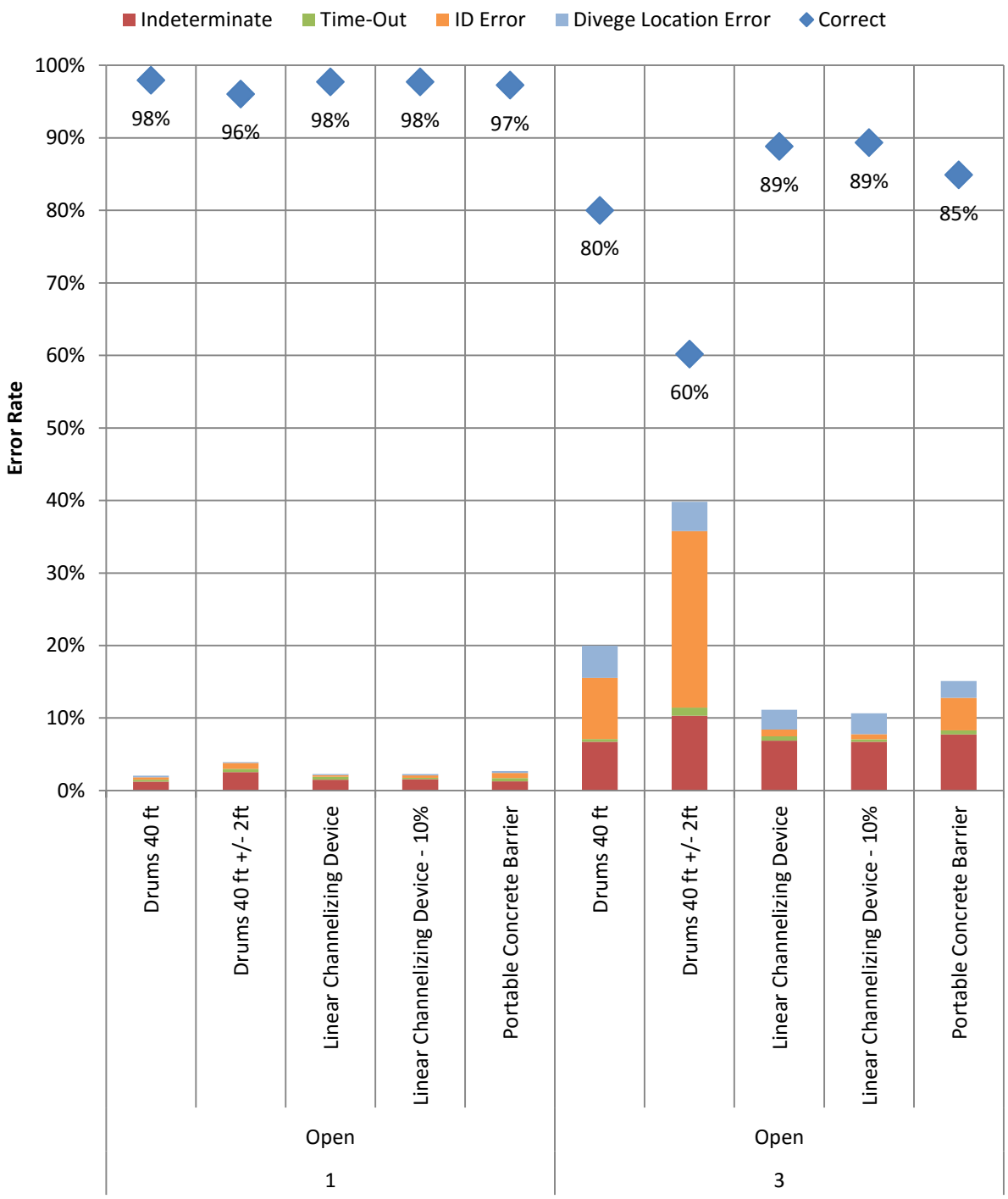

Figure 4-11 Experiment 3 – Percent Errors for Open Condition
(Numbers below the blue diamonds indicate the percent of correct responses.)

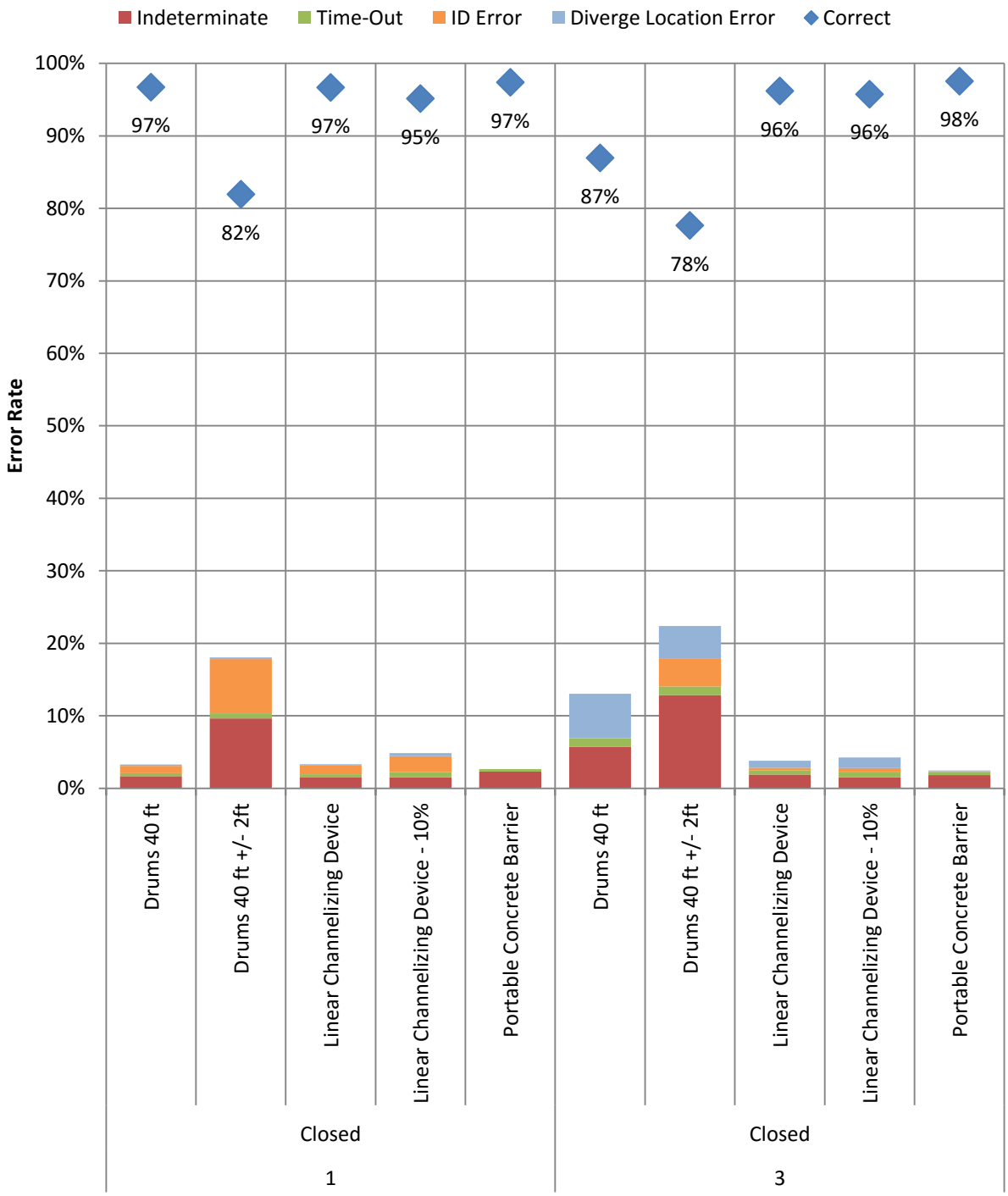

Figure 4-12 Experiment 3 – Percent Correct and Errors for the Closed Condition (Numbers below the blue diamonds indicate the percent of correct responses.)

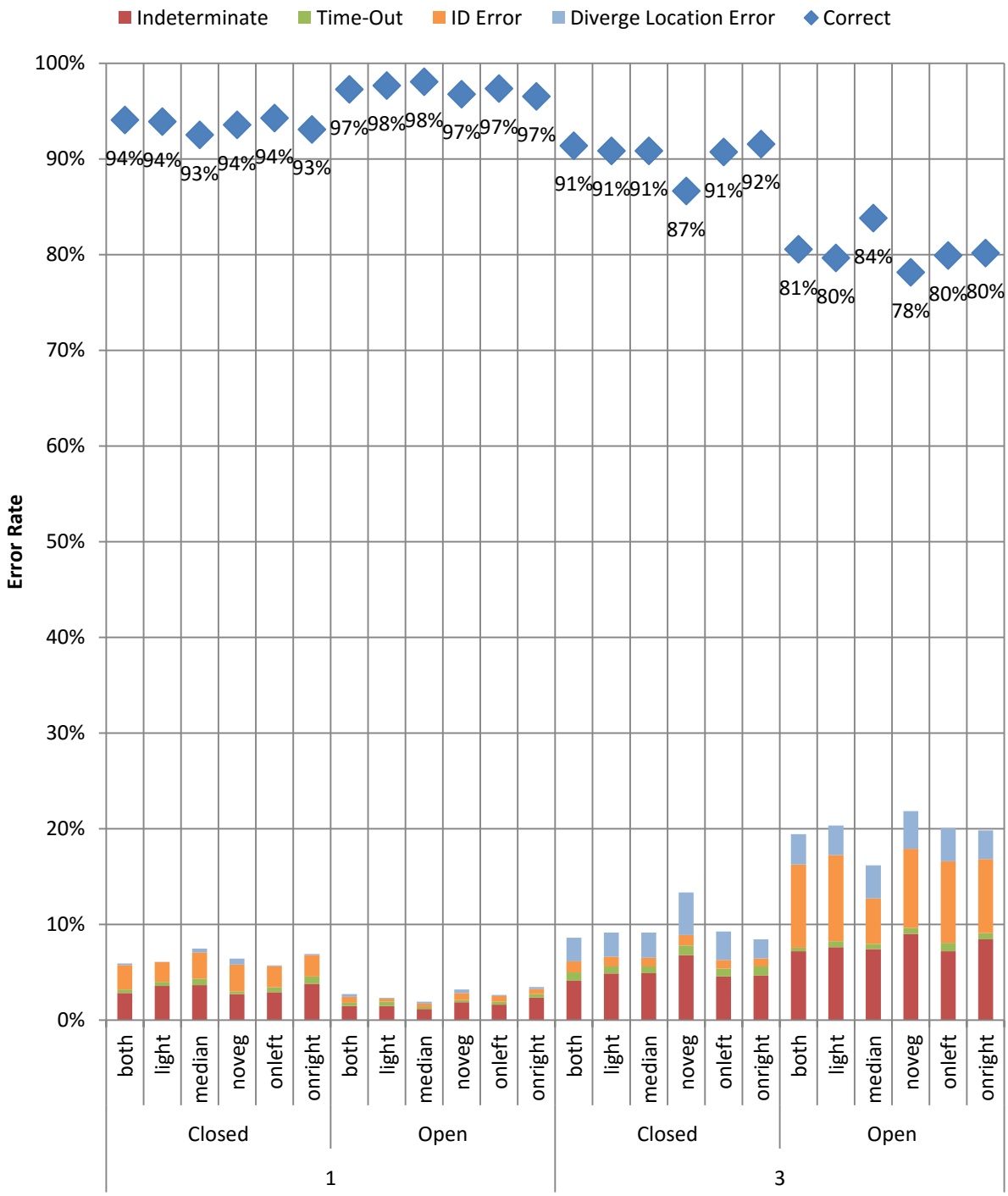

Figure 4-13 Experiment 3 – Percent Errors by Vegetation
(Numbers below the blue diamonds indicate the percent of correct responses.)

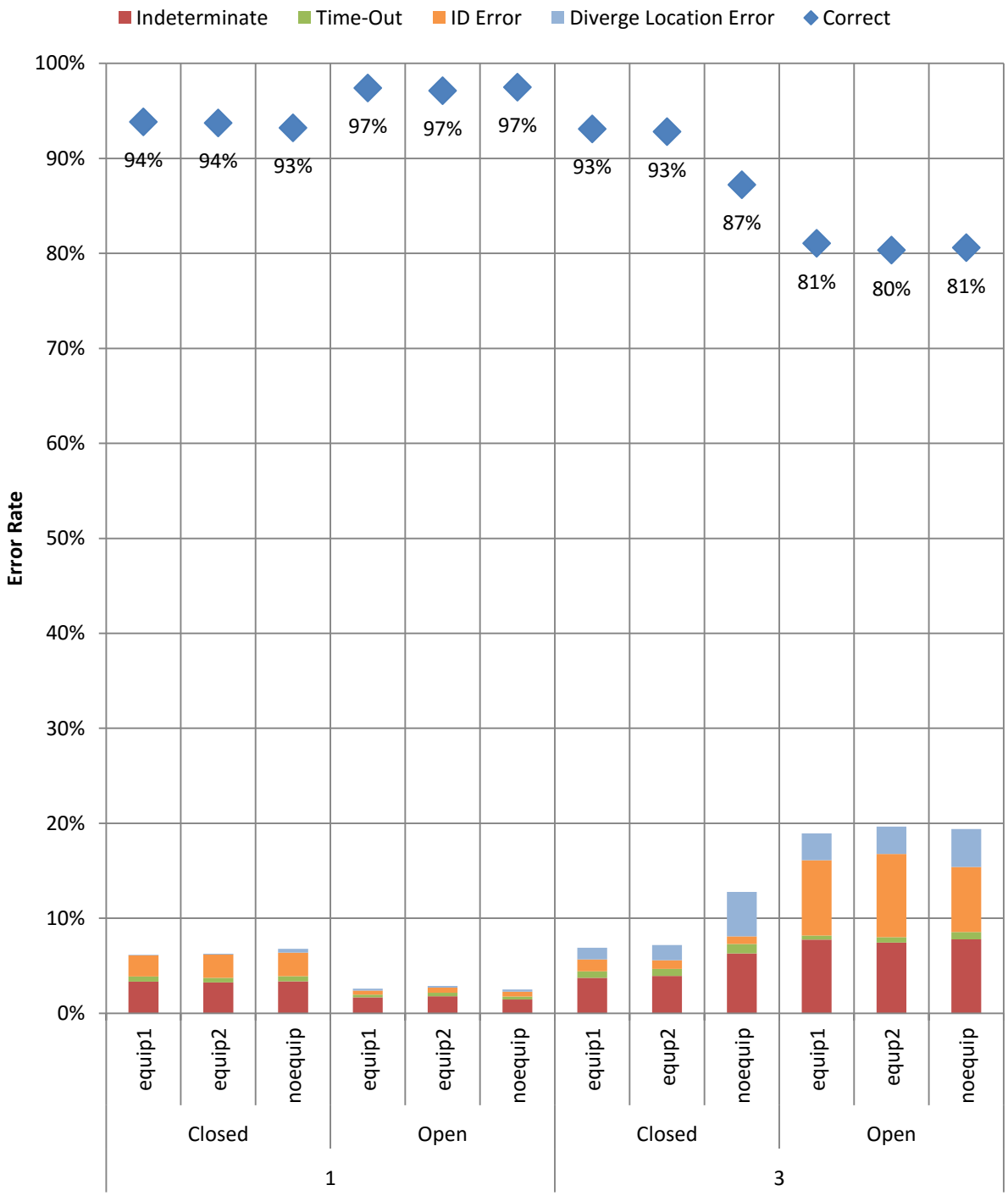

Figure 4-14 Experiment 3 – Percent Errors by Equipment
(Numbers below the blue diamonds indicate the percent of correct responses.)

4.3.3 Correct Response Latency

The correct response latencies from Experiment 3 are presented in Figure 4-15. The latency results from Experiment 3 align well with previous results from Experiments 1 and 2:

- Closed ramp scenarios feature longer average latencies than open ramp scenarios. This observation may suggest that participants are looking to respond "open" first, and, if the ramp is not open, they require additional time to respond.
- When the ramp is open, LCDs have shorter latencies than PCBs.
- When the ramp is closed, LCDs are more similar in performance to 40 ft. Drums. LCDs show shorter latencies compared to 40 ft. ± 2 ft. Drums, as well as less between-participant variability.
- Across all ramp setups and times-to-exit, the channelizing device 40 ft. ± 2 ft. Drums results in the worst performance, as seen by the longest latencies and highest level of between- participant variability.

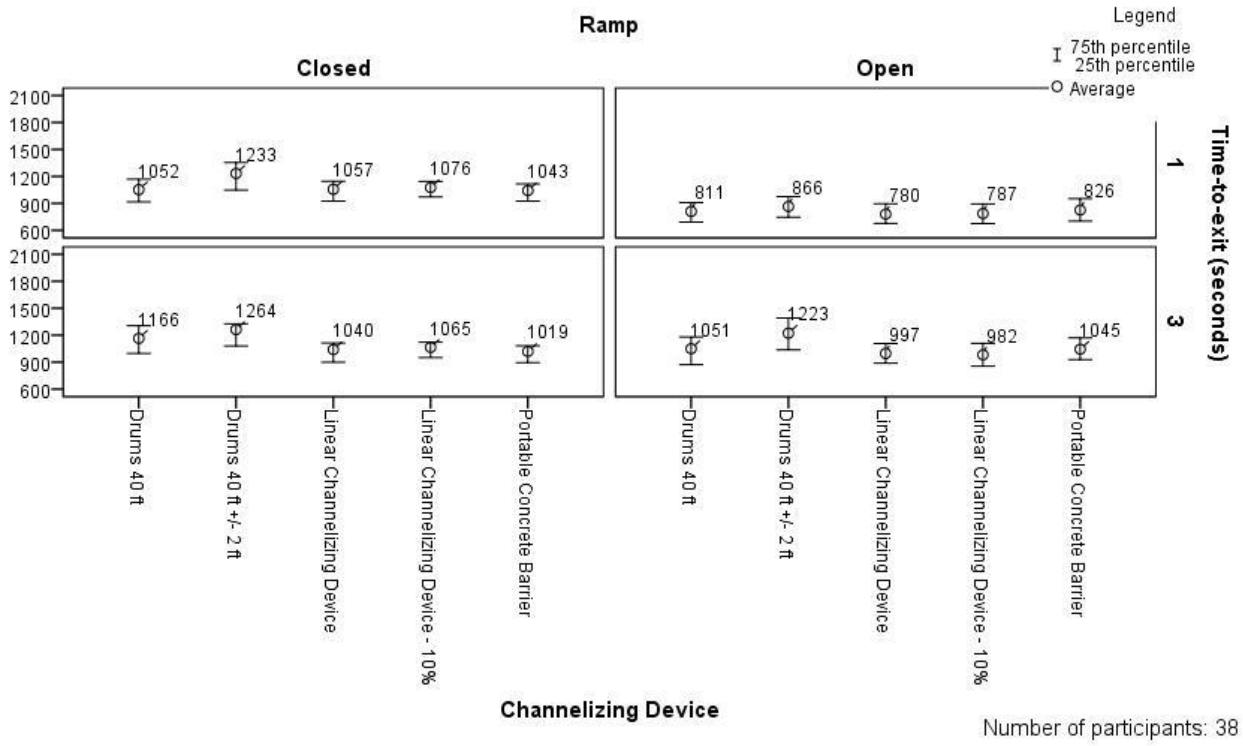

Figure 4-15 Experiment 3 – Correct Response Latency in Milliseconds by Channelizing Device

4.3.4 Discussion

Experiment 3 introduced varying roadside environments with regard to vegetation and work zone equipment. The results from Experiment 3 are comparable to those from Experiments 1 and 2.

Figure 4-16 is a radar chart depicting a comprehensive comparison among the channelizing devices tested in Experiment 3.

In Experiment 3, PCB, LCD and LCD missing 10% of pylons showed nearly equivalent performance in the percent correct, identification errors, and correct response latency. PCB resulted in the lowest Diverge Location errors; LCD and LCD missing 10% of pylons ranked slightly lower. Drums at 40 ft. ± 2 ft. resulted in the worst performance in all measures except for Diverge Location errors in which 40 ft. Drums resulted in the greatest errors rate. This experiment increased the realism of the images by introducing roadside vegetation and work zone construction equipment. Under these more realistic conditions, traffic control devices that best follow the principles of closure and continuity continued to provide the best performance, further strengthening the case for implementing traffic control with these features.

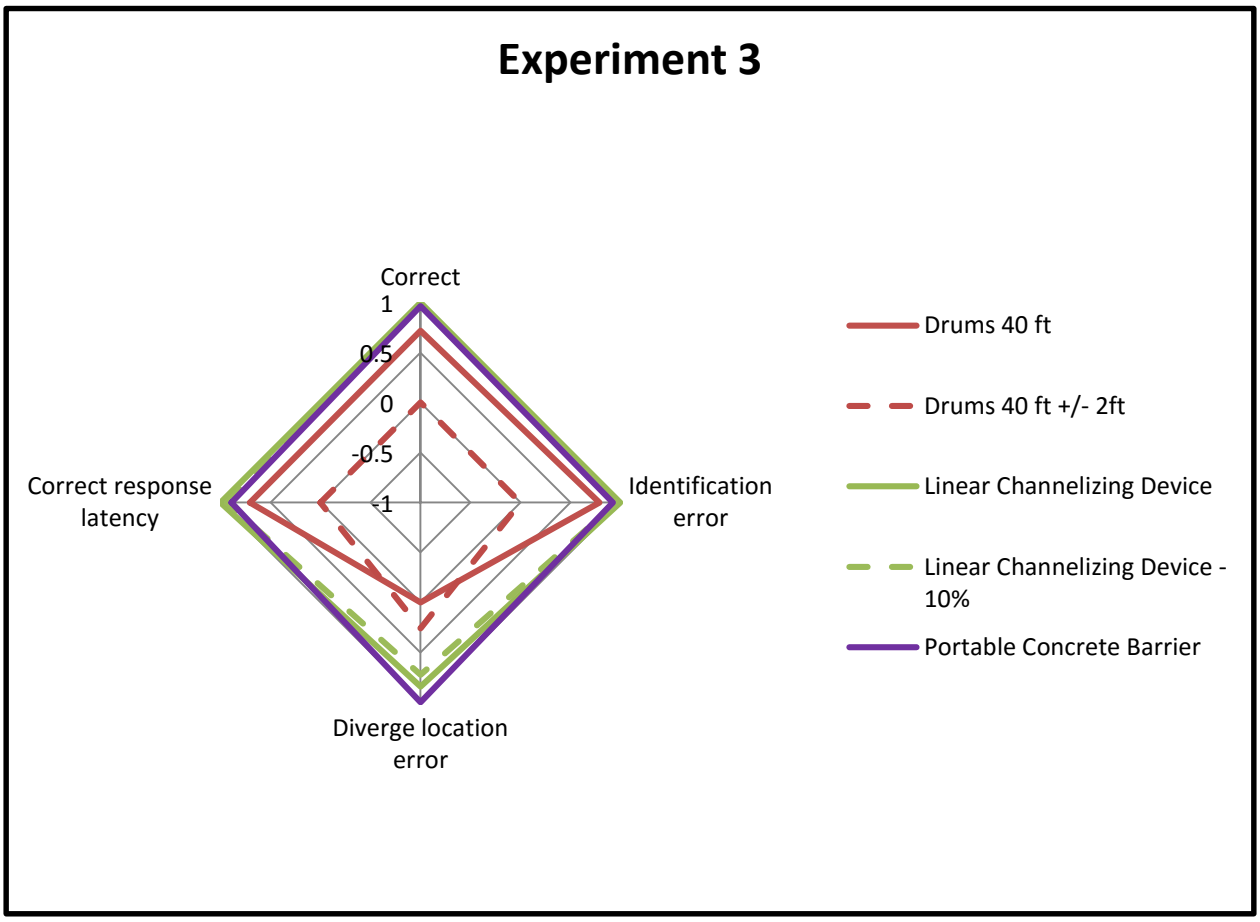

Figure 4-16 Comprehensive Comparison of Channelizing Devices in Experiment 3

5 Discussion and Conclusions

5.1 Findings

Each of the experiments in this research project approached the issue of delineation in work zone diverges with varying combinations of devices and configurations, and the results regarding each channelizing device were relatively consistent across experiments.

In almost all circumstances under open ramp conditions PCB, LCD, and LCD missing 10% of pylons resulted in better human performance than the drum alternatives. The drums at 10 ft. and 40 ft. spacing tended to perform similarly, although at a level below that of the PCB and LCD alternatives. This implies that there is likely minimal advantage between the drum spacings considered. The drum alternative with ± 2 ft. misplacements almost always resulted in significantly lower percent correct than other channelizing devices. As distance to the diverge increases, the differences between treatments becomes more discernible. Similar results were seen under ramp closed conditions with the exception that under longer time-to-exit distances LCD and well-aligned drum options tended to show similar Identification error rates. This may imply that when a construction project requires the full closure of a ramp then PCB may be the best option.

In addition, the impact of roadside vegetation and equipment was not discernible in most situations. However, at a significant distance from the diverge when the ramp was closed, scenarios without equipment showed greater errors. This observation indicates that the presence of equipment may provide additional cues signaling active work zones to drivers. Drivers may find empty work zones without active construction to be more difficult to interpret than work zones with active work. Interestingly, this finding aligns well with earlier research conducted by Daniel et al. (Daniel, Dixon and Jared 2000) that reviewed crash data at Georgia work zones and found that most crashes occur while the work zones are idle.

5.2 Closure and Continuity

As seen, the study results follow the Gestalt principles very closely, especially those of closure and continuity.

5.2.1 Closure

The principle of closure, as it applies to these circumstances, suggests that images that overlap in the visual scene may be perceived as a group. The portable concrete barriers are constructed to appear as a single object and the benefits of that configuration were readily seen. Similarly, the drums are perceived to overlap each other when they are far down the road, but are not perceived to overlap at shorter times-to-exit. This can even occur when the drums from the taper sections

overlap with drums from the tangent section and, thus, give the impression of a single mass of drums. Finley, Theiss, et al. (2011) reported this feedback when using closely spaced drums.

For Experiment 1, the impact of closure (or lack of closure) can most easily be seen in the closed condition. Here, the PCB alternatives resulted in participants making few errors in the 5, 4, 3, and 2 second times-to-exit on the straight geometry. The increased errors resulting from the drum alternatives were dominated by Diverge Location errors, where participants selected within the active work zone as the diverge location. However, these errors were not nearly as prevalent in the open condition, and no statistical differences existed between alternatives. This suggests that the break in closure from nearby drums may have incorrectly cued some participants that the opening between the drums was the ramp location.

Results from Experiments 2 and 3 reinforce the impact of closure with comparable results between the PCB and LCD alternatives. Indeed, LCD was designed following results from Experiment 1 regarding the impact of closure and continuity. By creating a device that could rapidly be grouped as a single unit through the principle of closure, LCD demonstrates how the results from PCB could potentially be applied with lower cost. Results showing no significant differences between PCB and LCD errors demonstrate that the benefits of closure from PCBs can be brought to work zones more cost effectively. However, it is important to clarify that LCD provides only the visual cues of PCB; it does not provide a similar physical barrier. LCD is easily traversable and will not redirect a vehicle encroaching into the work zone. Where the physical barrier attributes of PCB are needed, then the proposed LCD will not suffice.

The elevated number of location errors in areas without solid closure can direct future research, but this finding also raises issues with existing standards. A short review of state standards and of the MUTCD suggests that states have focused on special ramp barriers in the immediate vicinity of a ramp, especially when the ramp is open. But many of the observed errors occurred when the ramp was closed, several hundred feet from the start of the ramp treatment. These errors suggest that not only is closure an important issue, but also that a temporary ramp configuration could have an impact on driver understanding at greater times-to-exit than can be accounted for using existing delineation methods.

5.2.2 Continuity

Continuity is the principle that objects forming a linear pattern will be perceived as a single entity. In these experiments, channelizing devices in the PCB, LCD, and 10 ft. and 40 ft. drum spacing alternatives could be placed in a perfect line with exactly the same spacing between each device. Only the 40 ± 2 ft. and 10 ± 2 ft. drum alternatives were not perfectly linear; in those alternatives drums deviated by up to 2 ft. in each direction.

The decrease in continuity for the ± 2 ft. alternatives significantly affected the percent of correct responses in several ways. First, in the open condition, participants were much more likely to

make an Identification error (i.e., to say the ramp was closed). This problem of increased Identification errors continued through most time-to-exit distances until very close to the diverge point (2 seconds and 1 second). In a driving environment, misunderstanding the state of an exit ramp even for a short time period could have a negative impact on safety. The decrease in continuity also affected the distribution of correct responses, leading, under most conditions, to a higher mean and/or larger distribution of response times even when a participant identified the diverge as correctly open or closed.

This issue of continuity is important since a number of treatments can result in device placement that is not perfectly continuous. Wind and gusts from traffic can shift drums as they are sitting on the road surface, construction equipment can slightly impact drums, etc. The data from this study are not sufficiently comprehensive to draw absolute conclusions, but the findings clearly imply that even a relatively small variation in channelizing device continuity may decrease the ability of drivers to immediately comprehend the condition and location of an exit ramp.

5.3 Latency Measures

One challenge in safety research is that incidents are rare occurrences. The small number of incidents relative to the large number of driving events makes it difficult to conduct meaningful statistical analyses. Even in the experimental environment, as designed in this research, the number of errors is only about one tenth of the number of correct responses. Therefore, safety researchers often resort to surrogate measures to further understand the complex interactions and potential impact of critical design factors. In this particular research, latency (i.e., the duration between the presentation of an image and the participant's click) is a natural surrogate measure. In this research, latency consists of two components—the human reaction time, and human movement time. Because the participants have to move the mouse back to the fixed location on the screen each time before the next image is presented, the mouse movement time can be seen as a constant within each zone. Hence, latency may be considered as the time required for a participant to interpret a scene. The longer latencies, in this case, suggest that a scene is more complex, making it difficult for a driver to interpret and come to a decision.

The analyses of correct response latencies highlight the following observations:

- LCDs and PCBs result in nearly equal correct response latencies when the ramp is open.
- Correct response latencies where LCDs are used are no worse than the correct response latencies where drums are used when the ramp is closed.
- Average latencies are longer when the ramp is closed.
- Drums ± 2 ft. not only result in longer latencies, but also in a greater level of between-participant variability.

5.4 Implementation

The significant reduction in errors and decrease in correct response latency associated with certain work zone traffic control devices suggests that implementing the findings of this research could improve safety for drivers in Georgia. These findings can be implemented in both near term construction practice improvements and through longer term development and implementation of the new linear channeling device.

1. *Improve standards and training for channelizing device placement tolerances and device placement maintenance.*

   The results of this study show a potential reduction in driver performance when drums are placed slightly out-of-line or at inconsistent spacing. Enforcing standards requiring that contractors maintain high placement accuracy for drums, particularly near ramp locations or other decision points, over the duration of a work zone's existence may reduce driver confusion and improve driver performance, resulting in improved safety. In addition, the development of standards and training material for State inspectors to monitor delineation device placement will aid in ensuring these new practices will be instituted and maintained over the long term.

2. *Build the Linear Channelizing Device for use in work zone diverge areas where the work zone duration does not justify portable concrete barriers.*

   Results from Experiments 2 and 3 provide evidence that the Linear Channelizing Device results in performance that is comparable to PCBs when the ramp is open, and performs no worse than the drums when the ramp is closed. Given the improved performance compared to drums, and potential reduced cost compared to PCBs, LCDs are worth further investigation through field testing as a promising candidate for delineating work zones at diverges.

5.5 Further Research

The research performed in this study demonstrates significant impacts from temporary traffic control devices on both accuracy and latency in the task of identifying the location of a diverge. While it is broadly assumed that improving perception resulting from the traffic control system will improve safety, safety is generally measured not in levels of perception and responses but in the number of collisions. Future research should evaluate the impacts of these and other traffic control device configurations in a driving simulator to allow for direct measurement of driver behavior. Similarly, this research focused heavily on design principles to improve perception at diverges in work zones, but diverges only make up a small portion of most work zones. Future work should focus on expanding these design principles and implementations to improve perception for drivers throughout work zones of varying levels of visual complexity.

6 References

AASHTO. 2011, 6th edition. *A Policy on Geometric Design of Highways and Streets.* Washington, D.C. : American Association of State Highway and Transportation Officals.

Bryden, J., J. Fortuniewicz, and L. Andrew. 2000. "Intrusion Accidents on Highway Construction Projects." *Transportation Research Record.* doi:10.3141/1715-05.

CalTrans. 2006. "Traffic Control System for Lane Closures on Freeways and Expressways." *Standard Plans, US Customary* (State of California Department of Transportation) Sheet T10.

Chen, H., H. Zhou, J. Zhao, and P. Hsu. 2011. "Safety Performance Evaluation of Left-side Off-ramps at Freeway Diverge Areas." *Accident Analysis and Prevention*, 605–612. doi:10.1016/j.aap.2010.08.019.

Coren, S., and J. S. Girgus. 1980. "Principles of Perceptual Organization and Spatial Distortion: the Gestalt Illusions." *Journal of Experimental Psychology. Human Perception and Performance* 6: 404–412. doi:10.1037/0096-1523.6.3.404.

Daniel, J., K. Dixon, and D. Jared. 2000. "Analysis of Fatal Crashes in Georgia Work Zones." *Transportation Research Record.* doi:10.3141/1715-03.

FHWA. 2009. *Manual on Uniform Traffic Control Devices.* Washington, D.C. http://mutcd.fhwa.dot.gov/kno_2009rlr2.htm.

Finley, M., B. R. Ullman, and N. D. Trout. 2006. "Motorist Comprehension of Traffic Control Devices for Mobile Operations." *Transportation Research Record: Journal of the Transportation Research Board* (Transportation Research Board of the National Academies) 37–44.

Finley, M., L. Theiss, N. D. Trout, J. D. Miles, and A. A. Nelson. 2011. "Studies to Determine the Effectiveness of Longitudinal Channelizing Devices in Work Zones."

Florida DOT. 2012. "General Information for Traffic Control Through Work Zones." *FDOT Design Standards FY 2012/2013* (State of Florida Department of Transportation) Index No. 600. Sheet 11.

GDOT. 2011. *GDOT Standard 9032B - Concrete Curb & Gutter, Concrete Curbs, Concrete Medians* . October. http://mydocs.dot.ga.gov/info/gdotpubs/ConstructionStandardsAndDetails/9032b.pdf .

Georgia DOT. 2011. "Chapter 6: Cross Section Elements." In *GDOT Design Policy Manual*, by State of Georgia Department of Transportation. http://www.dot.ga.gov/doingbusiness/PoliciesManuals/roads/designpolicies/Pages/DesignPolicyManual.aspx.

Iragavarapu, V., and G. L. Ullman. 2012. "Benefit-Cost Analysis of Portable Concrete Barrier Use in Work Zones to Protect Against Intrusion Crashes." *91st Annual Meeting of the Transportation Research Board.* Washington, D.C.: National Academies of Science.

Johnson, J. 2010. "Designing with the Mind in Mind: Simple Guide to Understanding User Interface Design Rules. Children." 200. http://books.google.com/books?hl=en&lr=&id=woVADVwtL1gC&oi=fnd&pg=PP2&dq=Designing+with+the+mind+in+mind&ots=vo7eeBASon&sig=V2ov3lai0ZQlRaR9zM93FbGu_Rw.

Khattak, Asad J., Aemal J. Khattak, and F. M. Council. 2002. "Effects of Work Zone Presence on Injury and Non-injury Crashes." *Accident Analysis and Prevention* 34: 19–29. doi:10.1016/S0001-4575(00)00099-3.

Khorashadi, A. 1998. "Effect of Ramp Type and Geometry on Accidents." Washington, D.C.

Kulp, J. H., and J. M. Florsheim. 1978. Traffic Control Element. United States Patent US 4083033 A.

Lu, J., N. Geng, and H. Chen. 2010. "Impacts of Freeway Exit Ramp Configuration on Traffic Operations and Safety." *Advances in Transportation Studies* 22: 5–16.

McCartt, A. T., V. S. Northrup, and R. A. Retting. 2004. "Types and Characteristics of Ramp-related Motor Vehicle Crashes on Urban Interstate Roadways in Northern Virginia." *Journal of Safety Research* 35: 107–114. doi:10.1016/j.jsr.2003.09.019.

Michigan DOT. 2008. "M1420a: Typical Temporary Traffic Control for a One-Lane Closure on a Freeway in Advance of a Gore Area at a Major Divergence, No Speed Reduction." *Maintaining Traffic Typicals*, Sheet 2 of 2.

National Work Zone Safety Information Clearinghouse. 2009. *Work Zone Fatalities.* http://www.workzonesafety.org/crash_data/.

NHTSA. 2013. "Traffic Safety Facts 2011." *DOT HS 811 754*, 232.

North Carolina DOT. 2006. "Right Lane Closures Thru Exit Ramps." *English Standard Drawings* (State of North Carolina Department of Transportation) Sheet 7 of 9.

NYSDOT. 2008. "Single Lane Closure Near Exit Ramp, Expressway/Freeway." *2008 Standard Specifications (US Customary)* (New York State Department of Transportation).

O'Shaughnessy, M. P., and W. A. Kayson. 1982. "Effect of Presentation Time and Gestalt Principles of Proximity, Similarity, and Closure on Perceptual Accuracy." *Perceptual and Motor Skills*, 359–362. doi:10.2466/pms.1982.55.2.359.

Pain, R. F., H. W. McGee, and B. G. Knapp. 1981. *NCHRP 236: Evaluation of Traffic Controls for Highway Work Zones.* Washington, D.C.: National Cooperative Highway Research Program.

Roadway Safety Consortium. 2010. "Guidelines on Ensuring Positive Guidance in Work Zones." http://www.workzonesafety.org/files/documents/training/courses_programs/rsa_program/RSP_Guidance_Documents_Download/RSP_Positive_Guidance_Download.pdf.

Theeuwes, J., and H. Godthelp. 1995. "Self-explaining Roads." *Safety Science* 19 (2): 217–225. http://www.sciencedirect.com/science/article/pii/092575359400022U.

Ullman, G., M. Finley, and J. Bryden. 2008. "Traffic Safety Evaluation of Nighttime and Daytime Work Zones." http://trid.trb.org/view.aspx?id=875318.

United Nations. 2011. "United Nations Decade of Action for Road Safety 2011–2020." Accessed January 12, 2013. http://www.un.org/en/roadsafety/.

Wang, Z., B. Cao, D. Weiping, J. Lu, and Z. Zhang. 2011. "Safety Evaluation of Truck-Related Crashes at Freeway Diverge Areas." *90th Annual Meeting of the Transportation Research Board.* Washington, D.C.: National Academies of Science.