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Experimental Designs for Tortoise Pacing Diversion Structures and Tortoise Guards Along Highway Barriers

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Abstract. – In a study to reduce Mojave Desert Tortoise (*Gopherus agassizii*) mortality along roadways, we tested the feasibility of structures that discourage tortoises from 1) walking or "pacing" along barriers or 2) crossing areas where gates or openings occur. The diversion designs we tested (one straight and one curved structure, each 7.6 m long) deflected tortoises away from fences at nearly the same rate as tortoises who continued walking along barriers despite the diversion (36.8% vs. 35.7%). No "tortoise guard" structures that we tested, similar to cattle guard structures, were 100% effective at preventing tortoises from crossing the opening. We identified essential characteristics of an effective "tortoise guard" such as minimum gap sizes in the structure and a construction design that allowed a tortoise to climb out of a trench under the structure.

Key Words. – Mojave Desert Tortoise; *Gopherus agassizii*; deflection barriers; mortality; endangered species; tortoise conservation

Efforts to respond to the "threatened" status of the Mojave Desert Tortoise (*Gopherus agassizii*) in the Mojave Desert (US Fish and Wildlife Service 2011) have included attempts to restore habitat by eliminating the effects of roadways and other hazards (Forman and Alexander 1998). Roads have long been identified as a source of mortality for the desert tortoise (Klauber 1932; Woodbury and Hardy 1948; Berry and Nicholson 1984; Boarman et al. 1997; von Seckendorff Hoff and Marlow 2002; Peadan et al. 2016). As tortoises wander their sometimes-extensive home ranges in their search of food or mates, they may encounter roadways. Additionally, roadways may attract tortoises because of enhanced forage plants in the adjacent areas (Boarman et al. 1997; Lovich and Daniels 2000; Grandmaison et al. 2010). Both surveys of tortoise sign including burrows and scats (Nicholson 1978; Boarman and Sazaki 2006; Nafus et al. 2013; Berry et al. 2014; Peadan et al. 2016, 2017), as well as experimental studies (Boarman et al. 1993; Boarman 1995), indicate that roadways effectively reduce or eliminate the adjacent tortoise population. Efforts to reduce mortality have explored the effectiveness of barriers along highways to prevent tortoise crossings while still maintaining gene flow through culverts and passageways under the highway (Boarman et al. 1997). In response to these findings, there have been tests for potentially effective barriers along roadways to discourage tortoise crossings (Fusari 1982; Ruby et al. 1994, 2023). As a strategy for habitat restoration, reducing the mortality caused by vehicular traffic increases the amount of habitat available (Fusari 1982; Berry et al. 2013, 2014), although Peadan et al. (2015) suggest the effect might be more significant along interstate and other heavily traveled roads.

Forman and Alexander (1998) described a road-effect zone on the vertebrate animals near a road or highway with the magnitude of the effect dependent upon the species and its biological characteristics (body size, age, locomotor ability, size of home range, and others). An effective barrier may be a structure that causes tortoises to change direction and travel away from the roadway. In addition, locations with gates or openings in the barrier require deterrents to crossing that tortoises recognize as impassable structures. Some evidence suggests that desert tortoises may avoid roads even without barriers (Peadan et al. 2017), while Grandmaison et al. (2010) and Lovich and Daniels (2000) suggested tortoises might be attracted to the edge of gravel roads.

Behavioral studies have noted the persistence of tortoise movement along an obstacle (Ruby et al. 1994, 2023; Peadan et al. 2017). This suggests tortoises increase their chances of finding gaps or weakness in barriers as they spend more time near a barrier. Tortoises may be conflicted between visual and tactile information about a barrier (Fusari 1982; Ruby et al. 1994), may walk away from the barrier when confronted with a barrier angle or corner, or continue around the end of a barrier. A visual cliff phenomenon is known in tortoises (Yerkes 1904; Patterson 1971; Granda 1989; Golubovic et al. 2013) and other turtles (Ashe et al. 1975), which must recognize cliffs and other vertical structures in their natural habitat. This suggests a strategy for possible deterrent structures.

This study was part of a project designed to provide a more accurate scientific and engineering basis for mitigation activities by Clark County, Nevada, USA, in protecting the desert tortoise along highways. Structures that reduce tortoise pacing or interactions with barriers might minimize the probability that the tortoise would find a weakness and escape through the fence or barrier. Here we tested 1) structures that encourage tortoises that are pacing the barrier by deflecting the animal's direction by placing diversion structures along a straight barrier, and 2) designs that prevent a tortoise's passage through gates or other gaps in the barrier. We focused on adult tortoises even though juveniles may differ in their responses. Reducing adult desert tortoise mortality would also have a stronger positive impact on population demographics (Doak et al. 1994; Heppell et al. 1996; Heppell 1998).

METHODS

We used the facilities at the Desert Tortoise Conservation Center (DTCC) near Las Vegas, Nevada, to conduct experiments examining the effectiveness of pacing diversion structures and tortoise crossing structures. Test structures were built during March and April 1995 and we conducted observations April–June 1995. We used 28 female adult desert tortoises ($\geq$ 180 mm median carapace length) held at the DTCC. Initially, we planned to test groups of both males and females. However, in our first test of 10 males, we found that males spent most of their time in agonistic encounters rather than interacting with the test structure. In each test, tortoises were moved from holding pens into the test pens for the duration of the experiment.

Experiments with Pacing Diversion Structures. — We designed two diversion structures and placed them opposite from each other on the same fence in two adjacent large pens (Fig. 1; one pen was 61 $\times$ 61 m and the other was 30 $\times$ 61 m) that were already established and available for use. One diversion structure was straight and oriented perpendicular to the existing pen wall while the other was smoothly curved. The diversion structures were solid barriers—31-cm-high galvanized rolled steel approximately 7.6 m long. Each large pen had $\geq$ 10 burrows to house the tortoises used for the test.

We made a permanent record of behavior near the pacing diversion structures using a wide-angle video camera mounted on a 3-m-high platform located above the

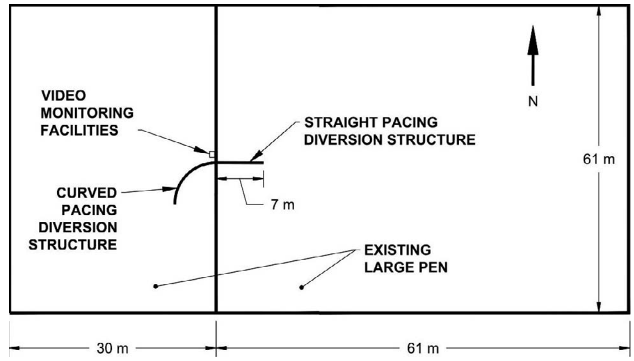

Figure 1. Experimental configuration of tortoise pacing deterrent structure. Straight and curved diversion structures were on opposite sides of the same barrier wall. Movement along the diversion structures by Mojave Desert Tortoises were recorded through video monitors placed above the structures during testing.

base of the test diversion structures. The camera field-of-view showed the entire pacing diversion structure and some additional space in the vicinity. The video camera recorded a frame every 1.2 sec, recording 72 hrs of observation on a conventional video tape. The recorder was turned off at night. Upon completing an experiment, we viewed the tape at a video workstation with slow motion capabilities. We recorded behavioral responses by tortoises that had encountered the diversion structure on a standardized datasheet using a set of standard definitions of possible reactions to the fence (Table 1).

We placed 10 adult female tortoises in one pen for a period of 5 d. We used only female adult tortoises; therefore, there was little social interaction and the pen sizes were large enough to allow free movement of the animals, compared with the test pens used in other experiments. Testing 10 animals at the same time reduced the length of the testing period. We replicated this setup twice for each pacing diversion type (straight and curved) for 4 runs total. Every female was tested with both diversion structures. We marked each tortoise for individual recognition by placing a strip of white tape in $\geq$ 1 of 4 positions on the carapace of each animal: anterior, left and right sides, and posterior. These strips of tape were visible in the video image.

Experiments with Crossing Deterrent Structures. — Deterrent structures were tested systematically to identify basic behavioral responses potentially useful in designing structures that discourage tortoises from crossing openings in the barrier. They were conceptually similar to a cattle guard, designed to allow human traffic across the opening but preventing animals from crossing. We cut a 2-m-wide gap in a common wall between 2 10 $\times$ 15-m pens at the DTCC (Fig. 2). Each pen contained $\geq$ 2 artificial burrows. A 0.7-m-deep trench at the gap in the fence was framed in wood (0.9 $\times$ 1.8 m) such that a set of planks 1.8 m long could be placed with varying sized gaps between the planks on top of the frame at ground level and would not impede a tortoise's travel if it tried to cross. Any tortoise

Table 1. Behavioral categories used to score Mojave Desert Tortoise responses to pacing diversion structures and crossing deterrent structures.

Behavioral category	Description of animal behavior
Diversion structures:	
Explore	Walks along structure and investigates it
Rebound	Meets structure, either (1) turns 180° there or (2) walks less than half way up structure before turning 180° and returns along pen wall
Follow and leave	Follows diversion structure, walks past half way point or goes to end and leaves area
Continue around	Follows diversion structure, goes around the end and walks along other side of diversion and resumes walking along the pen wall
Retrace	Meets structure, walks along length of diversion and then turns 180° and returns to pen wall
Crossing deterrent structures:	
Walks by (ignore)	Walks by structure but little or no attention
Cross (aborted)	Attempts crossing and walks on it but aborts attempt
Cross (success)	Successfully crosses structure
Easy cross	Crosses structure without hesitation
Difficult cross	Crosses structure but shows hesitation or has trouble
Stuck or falls	Becomes stuck in barrier for $\geq$ 1 min or falls through opposite side of structure

walking between the two pens had to cross over this structure.

We conducted two tests to evaluate general behaviors to our deterrent structures. The first test was a "visual cliff" test using a clear plexiglass sheet that tested whether tortoises perceived the gap in the ground as an impassable structure. Second, we constructed a series of wooden structures modeled after a cattle guard but with gap widths of 0 (gap test control), 2.5, 5.1, and 7.6 cm to identify gap sizes that stop tortoise crossings. We tested each gap size for 2 d, starting with a gap of 0 cm, and then widened the gap longitudinally along the crossing structure for the next trial. Other tests evaluated specific, practical structures, including a standard size cattle guard constructed from plywood (7.1-cm-wide planks separated by 10.9-cm gaps), a "tortoise guard" constructed from wood (5.5-cm-wide planks separated by 3.3-cm gaps), and an olfactory barrier consisting of two creosote-treated railroad cross ties. Ruby et al. (1994) had noticed that tortoises seemed repulsed by the odor of a railroad tie barrier, which they tested.

We placed 2 adult female tortoises in each pen for 18 d and tested 9 different structures for 2 d each. We replicated this process with 4 new tortoises. We used only female animals because agonistic interactions between males could have biased tortoise crossing behavior. Tortoises were marked with white tape for individual recognition on the video tape (same as diversion experiment above). We monitored experiments using a time-lapse video system with a wide-angle video camera on a post 3 m above the crossing deterrent structure. The camera field-of-view covered the entire crossing structure plus space on either side. A time-lapse recorder recorded a frame every 1.2 sec, recording 72 hrs of data on a conventional video tape. The recorder was turned off at night. After completing an experiment, we viewed the tape at a video workstation with slow motion capabilities. We recorded data on a standardized datasheet and categorized the observed behaviors (Table 1). If a tortoise crossed a deterrent structure, we subjectively scored crossings as easy (animal crosses quickly or without hesitation) or difficult (animal crosses structure but shows hesitation or trouble with footing).

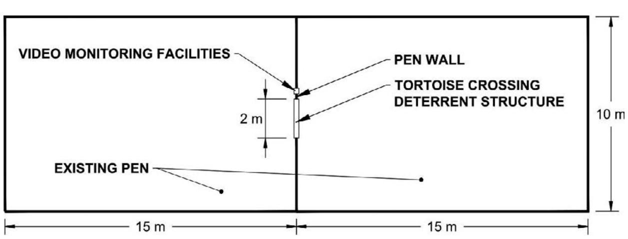

Figure 2. Experimental configuration of Mojave Desert Tortoise crossing deterrent structures. Different structures were placed in the opening between the two pens for 2 d each to test tortoise crossing rates as described in the text. Video recording occurred in the area of the deterrent structure during each test.

We maintained daily journal notes throughout the project. Daily information included the names of researchers, the starting pen number for behavior observations, shaded air temperatures at 1.5 m, 1 cm, and on the surface, weather conditions at 0800, 1200, and 1600 hrs Pacific Standard Time, and general observations and notes not recorded elsewhere.

RESULTS

Experiments with Pacing Diversion Structures. — Pacing diversion structures produced roughly three equally common responses (Fig. 3). The two movements of "continue around" and "follow and leave" were roughly equally common and "rebound" and "retrace", combined, accounted for the remaining third (Fig. 3). Tortoises changed direction along pacing diversion structures 73.9% and 93.6% of observations along straight and curved pacing diversion structures, respectively.

Experiments with Crossing Deterrent Structures. — Tortoises crossed all tested deterrent structures with a wide range in success rate (Table 2; Fig. 4). Tortoises were generally able to cross our opening ($>$ 75%) if the structure supported their movement (Fig. 4). The most successful deterrents were the visual cliff (4.3%) and the

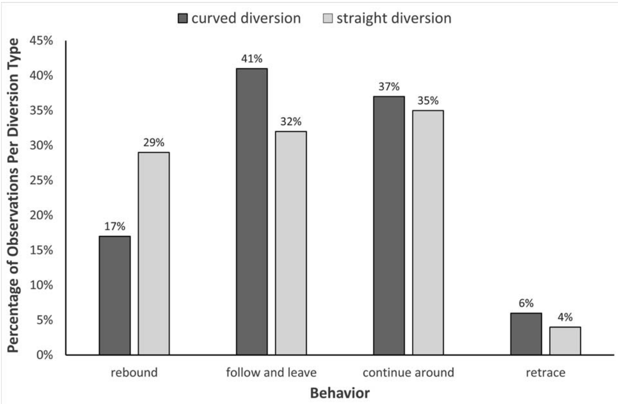

Figure 3. Percentage of Mojave Desert Tortoise behavioral responses for two pacing diversion structures. The diversion structures were galvanized metal 7.6 m long and placed perpendicular to the barrier wall. Sample size: n = 92 for straight and n = 126 for curved structure.

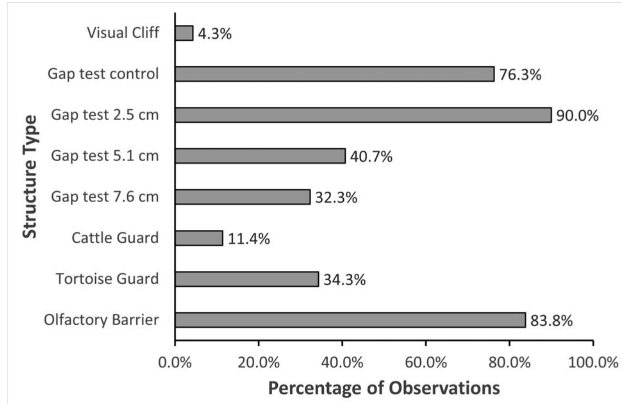

Figure 4. Success rate of traversing crossing deterrent structures by Mojave Desert Tortoises (n = 385).

cattle guard simulation with its 12-cm gap (11.4%). The tortoise guard with its 6-cm gap width was much less successful in deterrence (34.3%). About half of the few successful crossings of the visual cliff structure were difficult (Fig. 5). Wider gaps in the deterrent structure increased difficulty in crossing. Among the practical designs, all crosses with the cattle guard simulation were difficult, while the number of difficult crossings with the tortoise guard structure was lower. Almost all crossings with the olfactory barrier were easy.

Tortoises spent proportionally more time exploring structures that they did not successfully cross, an inverse relationship (Fig. 6). For the tests with the visual cliff, wider gap sizes ($\geq$ 5.1 cm), and the tortoise guard, about 30%–40% of the observations included exploratory behavior. The gap control structure, small gaps and olfactory barrier produced little exploratory behavior. Three other behavioral categories (rebound, walks by, and cross aborted) had no discernible trends.

We observed several crossings (n = 13) where we determined how animals thwarted the deterrent. In 4 of 5 cases with the visual cliff, crosses occurred along a small ledge about 3.8 cm wide between the existing fence and the surface of the visual cliff. In the fifth case, the tortoise began the cross along this ledge but completed the cross near the center of the structure after apparently discovering that it could walk on the plexiglass surface. The same individual performed 3 of 5 crosses and 2 different individuals performed the others. With the cattle guard structure, in 7 of 8 (87.5%) cases the crossing was begun along this same ledge. In 2 of the 7 cases, the tortoise started at the ledge and moved to the nearest cross beam and continued the crossing along this beam. In only one case did the tortoise originate and complete the passage along the cross beam. Three of the 8 crosses were by 1 individual and the other 5 crosses by 5 different animals. One tortoise became stuck in the crossing deterrent structure. The animal's limb became lodged between the slats in the tortoise guard structure for several minutes. The animal freed itself and was uninjured.

Tortoises fell into the pit under the crossing structure on 6 occasions, all with the cattle guard simulation, which had the widest gap spaces. In 5 of 6 cases, the animal escaped the 0.7-m-deep pit by climbing out and in the sixth case, a researcher removed the tortoise from the pit. In one incident, an animal fell into the pit in the morning and escaped in the early evening, 8.5 hrs later after many attempts to climb out. During the midday, this animal

Table 2. Behavioral responses of Mojave Desert Tortoises to a variety of crossing deterrent structures. We presented animals with a visual cliff, different-sized gaps, or potential structure designs. Each structure type is described in the "Methods". If the crossing was successful, we rated whether the crossing occurred easily or with difficulty.

Structure type	n	Explore	Rebound	Walks by	Cross aborted	Cross success	Stuck or falls	Easy cross	Difficult cross
Visual cliff	117	47	31	22	12	5		2	3
Gap test									
Control (0 cm)	38		2	5	2	29		29	
2.5 cm	30			2	1	27		27	
5.1 cm	27	8	4	3	1	11		6	5
7.6 cm	31	15	1	2	3	10		3	7
Cattle guard	70	33	11	11	2	8	5		8
Tortoise guard	35	11	7	3	1	12	1	8	4
Olfactory barrier	37	1	2	3		31		30	1
Total	385	115	58	51	22	133	6	105	28

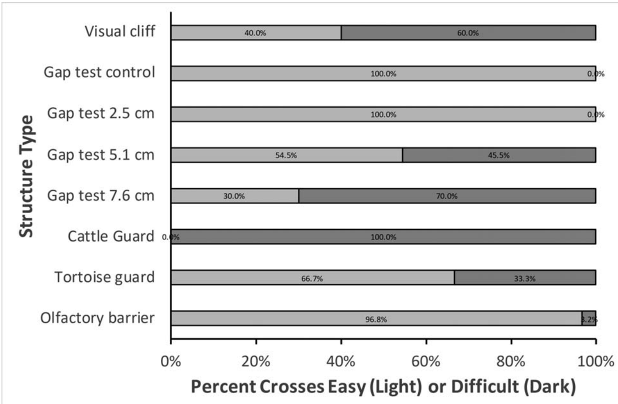

Figure 5. Percentage of difficult and easy crosses for the deterrent structures by Mojave Desert Tortoises. Categories are subjective. Easy crossings were made quickly and without hesitation. Difficult crossings involved more hesitant behavior or struggles making the crossing.

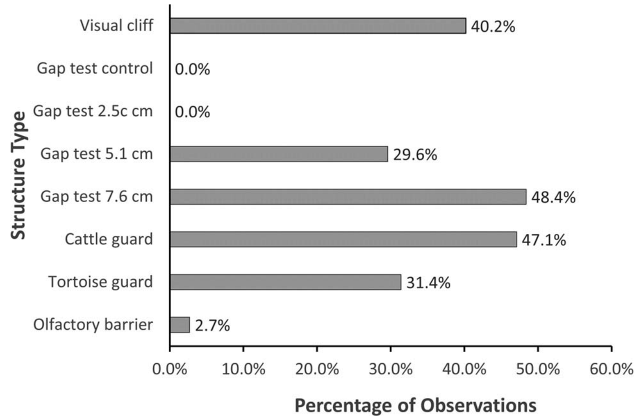

Figure 6. Rate of exploration behavior by Mojave Desert Tortoises in crossing deterrent structures (n = 385).

rested in the shade of the structure, limiting its escape attempts to the cooler portions of the day.

DISCUSSION

Our pacing diversion and deterrent structures that we tested were only partially successful in the goal of discouraging tortoise movement against barriers or avoiding areas with gaps in the barrier. We had anticipated 2 uses for pacing diversion structures: 1) periodic placement along barriers to discourage tortoises when encountering a barrier from walking along it for long distances; and 2) placement at a location where a barrier ended, such as where a fenced roadway met an unfenced roadway, or a gate or where another gap existed. The pacing diversion structure might be placed at the end of the barrier to deter tortoises from getting to the roadway side of the barrier (Reses et al. 2015). We considered the pacing behavior we hoped to reduce or minimize when a tortoise encountered a barrier as undesirable behavior for several reasons. First, encounters with barriers cause the animal to waste its energy. Second, pacing behaviors at barriers dramatically increase the likelihood of escape through the barrier (Ruby et al. 2023). And third, tortoises that spend time at barriers may experience thermal stress as body temperatures rise (Brand et al. 2016; Peadan et al. 2017).

Our pacing diversion configurations did not discourage tortoises from remaining near the barrier wall. "Continue around" could be considered a failure of the structure because tortoises were not deflected away from the barrier but pursued the same direction and continued pacing after rounding the diversion structure. The "follow and leave" pattern may represent effective deflection of the animal from the proximity of the barrier wall. These data illustrate the persistence with which tortoises move in a particular direction. Another factor in our response rates was the use of sheet metal (an opaque barrier). Based on the results of this experiment and tortoise behavior with respect to various barrier types (Ruby et al. 1994, 2023), we have no reason to expect that other materials such as hardware cloth or wire mesh fencing would be more successful. We only tested shape and length of the diversion structure. Our two shapes, a straight and curved structure, had similar but ineffective results, suggesting that shape of the diversion was not a significant variable in directing animals. Our tested structures were 7.6 m long. Shorter structures would probably be less effective in redirecting tortoise movements but we cannot predict the effectiveness of substantially longer structures. Intuitively, longer structures might increase the deflection rate but not to a degree to warrant implementation on a large scale. However, the persistent direction in movement that we observed in tortoises might be utilized to direct individual animals toward culverts and passageways along and under highways. Boarman (1994, 1995) noticed some culvert use by tortoises and Todd et al. (2016) noted a tendency for tortoises to utilize areas with washes more than flat open areas, which suggests barriers that direct tortoise toward culverts along highways might be successful.

Tortoise crossing deterrent structures were envisioned to be used like smaller scale cattle guards where unfenced sections of roadways, such as gates, intercept a fenced roadway. Our experiment suggests some characteristics of an effective design. Most importantly, tortoises will respond to a visual cliff as an effective barrier. Several crossings were by the same animal, so past experience may reduce the effectiveness of the visual cliff deterrent. Further, a gap width of 12 cm will probably prevent tortoises from crossing structures but animals will exploit any walkable area in the structure. However, we found an inverse relationship between structures that tortoises could not successfully cross and the amount of time they spent exploring it. In the visual cliff experiment, a small ledge 3.8 cm wide between the existing fence and the test structure was sufficient for a tortoise to make a successful crossing. In the cattle guard simulation, a 10.2-cm-wide structural beam perpendicular to the gaps in the structure allowed animals to cross.

Although the 12-cm gap width prevents tortoises from crossing, animals can still fall through at this width and did so in our experiment several times. An effective gap that prevents tortoises from crossing must be large enough to allow them to fall through. Animal experience with terrain may influence this behavior—Golubovic et al. (2013) found *Testudo hermanni* tortoises from a Greek site with rough terrain would jump off a simulated 50-cm-high cliff based on natural experience with the terrain but animals from a more level site did not. We were surprised that tortoises were able to climb out of the 0.7-m-deep pit under our deterrent structures. In designing a crossing deterrent structure, the animal could be prevented from gaining access to the highway side of the barrier system by making the pit deep on the highway side and shallower on the habitat side so it could easily climb out.

Based on the results of this experiment, an ideal tortoise guard has the following characteristics: 1) the barrier must protrude onto the structure to prevent any ledges around the edge of the structure, 2) the gap width between structural elements should be about 12 cm, 3) there can be no structural elements at the surface parallel to the direction of travel of tortoises, and 4) the pit below the structure should be shallower on the habitat side than the highway side in case tortoises fall in (a depth of 30 cm on the habitat side and 90 cm on the highway side would likely be effective). Although the results of the various test structures suggest a design that we think would be effective, the design should be experimentally confirmed prior to implementation.

Culvert usage, when combined with effective fencing, has been shown in a number of tortoises and turtles (Aresco 2005; Markle et al. 2017; Heaven et al. 2019; Read and Thompson 2021; Waltham et al. 2022) but further research on their long-term effects is needed (Lesbarreres and Fahrig 2012). These structures are intended to assist animal movement safely where roadways provide barriers. Culverts can also cause mortality of desert tortoises (Lovich et al. 2011). Our experiments show that diversion structures that deflect or redirect tortoises may not work very effectively in light of persistent travel direction by tortoises. Gaps in the fencing along roadways caused by gates, incomplete fencing, and poor maintenance represent another challenge. Cattle guards can be effective barriers at gates, but there is the concern that tortoises may not be able to climb out of the underlying trench.

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