Strategies for Ungulate-vehicle Collision Mitigation

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Abstract

Wildlife mortality caused by vehicles presents a serious conservation and economic problem, as collisions with large mammals are global, pervasive, and increasing. The combination of increasing ungulate populations combined with increasing vehicle-miles traveled has heightened the significance of this problem. We reviewed the U.S. and, secondarily, European scientific literature pertinent to mitigating the effects of ungulate-vehicle collisions. This review presents an analysis of ungulate movement and behavior in relation to roads to further develop general conclusions about accurately locating high frequency collision areas. Some successes in reducing ungulate-vehicle collisions have been documented with fencing, modified fencing, and grade separation via crossing structures, although traditional solutions often are expensive, e.g., fencing, overpasses, have limited effectiveness, e.g., reflectors, static warning signs, or may further habitat fragmentation or create barriers to movement, e.g., ungulate-proof fencing, vegetation clear-zones. We also present several case studies illustrating animal-detection driver-warning systems, technology based deployments, applied to the problem of ungulate-vehicle collisions. Although there is significant interest and potential in animal-detection driver-warning systems, many technical issues must be addressed before they are ready for general use. We emphasize the need for more sound statistical design in determining efficacy of treatments.

Key words: accident, crossing structures, deer, highway, intelligent transportation systems, mammalia, mitigation, mortality, roadkill, transportation, wildlife.

Introduction

Roads affect biological systems, communities, and species in numerous ways. Some conservation scientists have identified road construction and maintenance in the U.S. as one of the most widespread forms of modification to natural ecosystems over the past 100 years (Noss and Cooperrider 1994, Trombulak and Frissell 2000). Many wildlife species depend on the preservation of large tracts of intact land, but roads often fragment these tracts. Foreman (2000) estimated that 22 percent of the contiguous U.S. has been altered by the nation's road network. Trombulak and Frissell (2000) provide an excellent review of the ecological effects of roads at the taxonomic level (but also see Foreman and Alexander 1998). Collisions with large mammals are an increasing problem on the roadways of the U.S., Europe, and Japan (Groot Bruinderink and Hazebroek 1996).

Results from a survey of the nation's natural resource agencies (n = 35 reporting mortality) indicated that deer (*Odocoileus spp.*) conservatively accounted for 538,000 collisions in the U.S. in 1991 (Romin 1994, Romin and Bissonette 1996). Conover et al. (1995) extrapolated these findings for the remaining states and estimated that ungulates account for 726,000 to 1.5 million

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collisions in the U.S. annually. Groot Bruinderink and Hazebroek (1996) estimated the annual number of collisions with ungulates in Europe to number 507,000. Population density is a principal factor affecting ungulate presence along roads, and increased populations have been correlated with increased ungulate-vehicle collisions (Puglisi et al. 1974, Sage et al. 1983). During the last century, many ungulate populations in the U.S. have recovered due to protection from overexploitation, land-use changes, and application of scientific management (Messmer 2000). For example, the nation's white-tailed deer (*O. virginianus*) population is burgeoning, from about 500,000 animals at the turn of the century to more than 20 million today (Cook and Daggett 1995, Hughes et al. 1996). The combination of increasing ungulate populations and increasing vehicle-miles traveled has heightened the significance of this problem. From 1985 to 1991, deer-vehicle collisions increased an average of 69 percent in the states of California, Illinois, Maine, Michigan, Minnesota, North Carolina, Utah, and Washington (Hughes et al. 1996).

Estimates of the magnitude of damage caused by wildlife are acknowledged to be conservative and inadequate to develop accurate conclusions concerning the scale and socio-economic consequences of ungulate-vehicle collisions (Groot Bruinderink and Hazebroek 1996, Messmer 2000). Such collisions can involve safety and economic impacts that include injuries, fatalities, property damage, increased insurance premiums, lost hunting revenue, and carcass removal expenses (Conover et al. 1995, Conover 1997). Approximately 230 fatalities and 29,000 human injuries occur annually in the U.S. although in Europe an estimated 300 fatalities and 30,000 injuries occur annually from ungulate-vehicle collisions (Conover et al. 1995, Groot Bruinderink and Hazebroek 1996). Conover et al. (1995) and Cook and Daggett (1995) estimated the total cost in property damage due to ungulate collisions in the U.S. to exceed $1.1 billion annually. Estimates for Europe are similar (Groot Bruinderink and Hazebroek 1996).

Many factors affect the spatial and temporal distribution of ungulate-vehicle collisions, particularly ungulate movement, behavior, habitat, and topography. Ungulate-vehicle collisions are not randomly distributed but frequently occur in predictable locations, often in relation to habitat or topographical configurations, which concentrate crossings along particular sections of a roadway (Table 1). Collisions between large mammals and vehicles increase when roadways are constructed through prime habitat or intersect ungulate migration routes (Reed and Woodard 1981). Vegetation and topography can work synergistically to funnel deer to predictable crossing areas. Foreman and Hersperger (1996) outlined three (of six) major types of flows across landscapes that prove pertinent to highway mortality. They include surface water in streams, wildlife in major corridors, and vehicles on roads. Indeed, Hubbard et al. (2000) found that bridges in Iowa "always indicate points where major edge-creating landscape features intersect roadways" and thus provided the best indicator of high incidence areas of white-tailed deer-vehicle accidents.

Roads change habitat complexes. Ungulates can be attracted to the road right-of-way because of palatable roadside plantings or increased production of under-story vegetation (Case 1978, Feldhamer et al. 1986, Waring et al. 1991). Bellis and Graves (1971) found that the number of white-tailed deer killed/month on Interstate 80 in central Pennsylvania was strongly correlated with numbers of deer observed grazing along the right-of-way. For white-tailed deer, the highway right-of-way is an "increasingly common, if not 'natural,' aspect of their environment" (Carbaugh et al. 1975). Early green-up of right-of-way vegetation was a primary cause of sika (*Cervus nippon*) deer-vehicle accidents in

Table 1. Published research regarding ecological relationships associated with ungulate mortality on roads, predominately for the United States.[1]

Reference	Species	Location	Habitat Type
Peek and Bellis 1969	*O. virginianus*	PA	Mixed hardwood
Carbaugh 1970	*O. virginianus*	PA	Mixed hardwood
Vaughn 1970	*O. virginianus*	PA	Mixed hardwood
Bellis and Graves 1971	*O. virginianus*	PA	Mixed hardwood
Puglisi et al. 1974	*O. virginianus*	PA	Mixed hardwoo
Reilly and Green 1974	*O. virginianus*	MI	Mixed hardwod
Carbaugh et al. 1975	*O. virginianus*	PA	Mixed hardwod
Mansfield and Miller 1975	*O. hemionus*	CA	Varied
Allen and McCullough 1976	*O. virginianus*	MI	Mixed hardwood
Goodwin and Ward 1976	*O. hemionus*	WY	Prairie
Kasul 1976	*O. virginianus*	MI	Mixed hardwood
Rost and Bailey 1979	*O.hem/C.e.can*	CO	Pine/Juniper/Shrub
Sicuranza 1979	*O. virginianus*	MI	Mixed hardwood
Kress 1980	*O. virginianus*	PA	Mixed hardwood
Sage et al. 1983	*O. virginianus*	NY	Mixed Hardwood/
Conifer			
Bashore et al. 1985	*O. virginianus*	PA	Mixed hardwood
Waring et al. 1991	*O. virginianus*	IL	Mixed hardwood/Ag.
Groot Bruinderink and Hazebroek 1996	Various	Europe	Varied
Calvo and Silvy 1996	*O.vir.clavium*	FL	Varied
Pafko and Kovach 1996	*O. virginianus*	MN	Mixed Hard./Conifer/Ag.
Gunther et al. 1998	Various	Yellowstone N.P.	Varied
Finder et al. 1999	*O. virginianus*	IL	Varied (GPS)
Iverson and Iverson 1999	*O. virginianus*	OH	Varied
Hubbard et al. 2000	*O. virginianus*	IA	Varied (GPS)
Rowland et al. 2000	*C. elaphus*	OR	Pine/Bunchgrass Forest

[1] After Romin and Bissonette 1996.

Japan (Kaji 1996). For the U.S. as a whole, elk (*Cervus elaphus*) and mule deer (*O. hemoinus*) are most vulnerable to highway collisions in winter when driven to lower elevations by snow accumulation (Leedy 1975). Moose (*Alces alces*) tolerate snow, but great depths can encumber movement and encourage moose to use plowed roads for travel (Garrett and Conway 1999). Moose also are particularly vulnerable to collisions in spring and early summer when leeching highway salts attract them to roadside pools (Fraser 1979, Fraser and Thomas 1982).

Ungulate presence, activity, movement, and behavior contribute greatly to high-incident collision locations. Generally, ungulate activity levels tend to be highest in early morning and evening, times of typically decreased visibility and increased commuter traffic (Putman 1997). Peek and Bellis (1969) correlated dawn and dusk peaks in collision numbers to increased deer movement during those times. Leedy (1975) noted that elk mortality due to vehicles occurred primarily at night. Haikonen and Summala (2001) found that the crash rate for moose and white-tailed deer in Finland was highest 1 hr after sunset. Although no ungulate is strictly diurnal, crepuscular, or nocturnal, all have proven sensitive to human disturbance and tend to avoid open areas during the day (Putman 1997). Ungulates can habituate to roadways and will regularly cross minor roadways during daily movements within their home ranges to reach favored foraging (Waring et al. 1991, Putman 1997) and resting areas (Carbaugh et al. 1975).

Vehicle collisions with ungulates also have been linked with breeding and dispersal activities (Jahn 1959, Case 1978, Feldhamer et al. 1986, Groot Bruinderink and Hazebroek 1996). Studies in Pennsylvania and Michigan suggested collisions with white-tailed deer peak during the autumn breeding season (rut), when both females and males are more peripatetic (Puglisi et al. 1974, Allen and McCullough 1976). There is usually another small peak in spring corresponding to parturition and dispersal of young (Reilly and Green 1974). In Pennsylvania, Feldhamer et al. (1986) documented that of 44 seasonal home range estimates for white-tailed deer, 16 (36.4%) included segments of I-84 or a secondary roadway during one or more seasons.

The importance of accurately identifying high crash areas cannot be understated, as the success of many mitigation measures depends on the accurate location of high incidence crash areas and the understanding of all factors that contribute to them (Table 1). As Putman (1997) states, "selection of the appropriate deterrent measures in any given situation is itself dependent upon proper understanding of the actual pattern of such accidents.... Without such biological understanding, we cannot really determine where preventative measures should be concentrated, or suggest *a priori* which of a variety of deterrent options is likely to be most effective in given circumstances." The remainder of this paper reviews the many research efforts, both past and present, which have attempted to reduce ungulate-vehicle collisions.

Review of Traditional Mitigation Methods

There have been numerous attempts to reduce large mammal mortality due to vehicles over the past few decades (Groot Bruinderink and Hazebroek 1996, Romin and Bissonette 1996, Putman 1997). Most researchers attempt to evaluate a single mitigation technique, which makes comparisons among techniques difficult (Table 2). Most of the literature suggests that many mitigation techniques have limited utility. Researchers applying traditional countermeasures have generally approached the problem of ungulate collisions with one or more of the following goals (1) reduce ungulate density in problem areas, (2) prevent or deter animal access to the road, (3) improve the motorist's ability to avoid a collision by elevating the motorist's awareness of the hazard.

Decreasing Ungulate Density

Local population density is one of the primary drivers of wildlife-traffic mortality (Finder et al. 1999, Joyce and Mahoney 2001). Allen and McCullough (1976) suggested controlling ungulate population numbers through harvest as one of the most effective means of reducing ungulate-vehicle accidents. Hunting has proven to be a fundamental and effective tool for managing ungulate populations. Sage et al. (1983) noted that hunting negatively influenced observation rates of white-tailed deer along forest roads in New York, largely because of reduced deer density. Spatial distribution of moose-vehicle collisions in Newfoundland depended on both traffic volume and local population density (Joyce and Mahoney 2001). Both Michigan and Illinois have used harvest in an attempt to reduce local populations and decrease ungulate-vehicle collisions (Romin and Bissonette 1996). Michigan indicated that hunting was successful (Romin and Bissonette 1996), whereas despite local population declines in Illinois, white-tailed deer-vehicle collisions did not subsequently decrease (Waring et al.1991). Inconsistencies such as these suggested that frequency of ungulate-vehicle collisions is not simply density dependent. Similarly, utility of highway mortality as an index of species population trends has been debated (Jahn 1959, McCaffery 1973, Loughry and McDonough 1995). According to Case (1978), ungulate-vehicle collisions are the function of the following parameters: population densities, seasonal behavior, traffic speed, traffic volume, and roadside vegetation.

Table 2. Examples of published literature assessing the efficacy of various traditional mitigation techniques in reducing ungulate-vehicle collisions (categories are not mutually exclusive).

Reference	Location	Mitigation Technique
Effective		
Reed et al. 1975	CO	Highway Underpasses
Ward 1982	WY	Highway Fencing and Underpasses
Ludwig and Bremicker 1983	MN	Highway Fencing and One-way Gates
Schafer and Penland 1985	WA	Swareflex Reflectors
Wood and Wolfe 1988	UT	Intercept Feeding
Jaren et al. 1991[1]	Norway	Vegetation Removal
Lavsund and Sandegren 1991	Sweden	Highway Fencing, Vegetation Removal
Foster and Humphrey 1995	FL	Highway Underpasses
Messmer et al. 1999	UT	Temporary, Seasonal Signage
Clevenger et al. 2001	Alberta, Canada	Highway Fencing
Ineffective		
Woodward et al. 1973	CO	Swareflex Reflectors
Pojar et al. 1975	CO	Lighted, Animated Deer Crossing Signage
Falk et al. 1978	PA	Highway Fencing
Reed and Woodard 1981	CO	Highway Lighting
Feldhamer et al. 1986	PA	Highway Fencing
Lavsund and Sandegren 1991	Sweden	Repellents (light, sound, and scent)
Ford and Villa 1993	CA	Swareflex Reflectors
Reeve and Anderson 1993	WY	Swareflex Reflectors
Ujvári et al. 1998	Denmark	WEGU Reflectors
Inconclusive		
Bellis and Graves 1971	PA	Highway Fencing
Puglisi et al. 1974	PA	Highway Fencing
Gilbert 1982	ME	Deer Mirrors
Pafko and Kovach 1996	MN	Deer Reflectors
Lehnert and Bissonette 1997	UT	Highway Crosswalk Structures

[1] Assessed efficacy on reducing moose–train collisions.

Limiting Ungulate Access

Management of ungulates on roads often consists of countermeasures designed to reduce crossing or change the pattern of crossing activity (Putman 1997). The goals of many countermeasures include altering, limiting, or preventing animal access to the roadway in areas exhibiting frequent collisions. Traditional countermeasures attempting to accomplish these goals include: (1) fencing, modified fencing, and grade separation through overpasses and underpasses to prevent animals from entering the roadway; (2) reflectors, scent repellents or sonic signals that temporarily arrest ungulate movement; and (3) vegetative plantings to alter ungulate movement patterns or the relative attractiveness of right-of-way versus non right-of-way vegetation.

Fencing, modified fencing, grade separation.—Building barriers, such as fences, is the most common approach to prevent ungulate-vehicle collisions (Cook and Daggett 1995). A variety of fences exist to address the problem and they vary in cost and effectiveness (Clevenger et al. 2001). Most of the fencing used to limit human access to high capacity freeways is 1.22 m woven or barbed wire (Cook and Daggett 1995). However, ungulates can readily jump such fences making ungulate-proof fencing necessary. Ungulate-proof fencing, generally 2.2 to 2.7 m high, is considered an effective restraint and is typically used to channel ungulates to crossing structures (Falk et al. 1978, Ward 1982, Cook and Daggett 1995). Although the literature offers no clear guidance on the length of ungulate-proof fencing (Foster and Humphrey 1995), fencing must be of sufficient length so as not to encourage end-runs (Ward 1982, Feldhamer et al. 1986). End runs occur when ungulates travel to the end of the fence and become trapped in the road corridor, often re-concentrating collisions. Because of this phenomenon, ungulate fencing is sometimes modified by additional one-way gates, which allow ungulates caught within the paved area to escape through the gate (Reed et al. 1974). Fencing is only effective when designs take local topography, snow accumulation, and need for maintenance into account (Ward 1982). Falk et al. (1978) documented white-tailed deer crawling through fence openings <23 cm wide. When considering fencing projects, engineers and biologists should realize that barrier fencing profoundly affects animal movement and is not always feasible or acceptable (Clevenger and Waltho 2000, Hourdequin 2000).

Overpasses, underpasses, and crosswalks are sometimes used in combination with fences to increase permeability across, over, or under the roadway. Grade separation is the process of channeling ungulate movement toward crossing structures, mainly through fencing, so that they pass over or under the highway rather than walking across it at grade (Cook and Daggett 1995). Several studies demonstrated that grade separation, through the use of overpasses and underpasses, effectively increased permeability of roads for many species of wildlife (Foster and Humphrey 1995,Yanes et al. 1995, Clevenger 1998, Clevenger and Waltho 2000, Gloyne and Clevenger 2001). However, target species might initially be reluctant to use crossing structures, e.g. mule deer (Reed et al. 1975); therefore, it is important to determine the design features of crossing structures that increase efficacy (Rodriguez et al. 1996).

Several studies demonstrated that structure dimension and location, nearby cover, and human activities influence use of any crossing structure by large mammals (Reed et al. 1975, Singer and Doherty 1985, Clevenger and Waltho 2000, Gloyne and Clevenger 2001). Generally, the larger and more open crossing structures are the most effective. Reed et al. (1975) recommend a height and width of 4.3 m or larger for ungulate underpasses with the shortest practical length. Reed et al. (1975) found that neither artificial lighting nor skylights increased the use of underpasses by mule deer in Colorado. A relatively inexpensive alternative to grade separation are crosswalks, which consist of a break in fencing (at grade), accompanied by signs that warn motorists of crossing animals. Lehnert and Bissonette (1997) estimated the cost of crosswalks for a 2 and 4-lane highway to be $15,000 and $28,000, respectively, as compared to retrofitting underpasses on those same highways to be $92,000 and $173,000.

Reflectors and repellents.—Wildlife reflectors do not physically block animals entering the roadway, but they purport to discourage animals from entering the road by creating a visual barrier via incident light reflected by headlights until vehicles have passed (Gilbert 1982). Typical systems consist of a series of reflectors mounted on posts installed at regular intervals along the roadside. Reflector systems are relatively inexpensive, estimated to cost $8,000 - $10,000/mile (Gilbert 1982). Several states have experimented with reflective devices though results were often mixed (Romin and Bissonette 1996, Putman 1997). Three types of reflectors exist: polished metal mirrors and WEGU reflectors (Walter Dräbing KG, Kassel, Germany) that reflect incident light from headlights (e.g. Gilbert 1982 and Ujvári et al. 1998, respectively), and Swareflex reflectors (D. Swarovski and Company, Tirol, Austria), which transmits incident light as a continuous visual barrier of red or blue-green light (e.g. Schafer and Penland 1985).

Gilbert (1982) noted that polished metal mirrors were ineffective in reducing deer-vehicle collisions in Maine, even though small sample size limited any formal conclusions. Swareflex reflectors reduced deer mortalities in Iowa (Gladfelter 1984) and Washington (Schafer and Penland 1985) but were unsuccessful in Colorado (Woodard et al.1973), Illinois (Waring et al. 1991), California (Ford and Villa 1993), and Wyoming (Reeve and Anderson 1993). Fallow deer (*Cervus dama*) in Denmark exhibited increasing indifference to WEGU reflectors, which suggested that they too are ineffective at reducing ungulate-vehicle accidents (Ujvári et al. 1998). Furthermore, Zacks (1986) questioned the notion that ungulates avoid the color red when the results from his experiment provided no evidence that white-tailed deer responded any differently to the presence of red Swareflex reflectors, white reflectors of the same geometry, or a headlight beam without reflectors. Ujvári et al. (1998) noted that reflectors are not a reliable method of reducing ungulate-vehicle collisions on a long-term basis due to technical limitations and ungulate propensity to habituate to reflectors.

Wildlife repellents exist in many forms and with many different repelling principles, but most applied to ungulate-vehicle crashes utilize high frequency sound waves or odors that are either unpleasant to the animal or frighten them. Sound repellents may be stationary or installed as ultrasonic whistles on vehicles (Romin and Dalton 1992). When motorists reach certain speeds, the whistles produce frequencies of 16 to 20 kHz, and in theory the tone warns animals of approaching traffic (Romin and Dalton 1992). However, Romin and Dalton (1992) failed to detect behavioral response differences in 150 groups of mule deer that were exposed to whistles in Utah. In Sweden stationary sounds of 70 dB and frequencies up to 50 kHz were employed, yet moose failed to respond to sounds <21 kHz (Lavsund and Sandegren 1991). Bomford and O'Brien (1990), in a comprehensive review of sonic deterrents in animal damage management, state "devices producing sounds other than communicative signals (alarm or distress) have no persistent effect on animals' space use or food intake." There also is evidence of habituation to sonic repellents with prolonged or frequent exposure (Bomford and O'Brien 1990, Lavsund and Sandegren 1991).

Scent appears to be a better deterrent for animals than sound, but Lavsund and Sandegren (1991) noted that scents have had limited effectiveness in reducing moose-vehicle collisions in Sweden. A research team at the University of Umea (Sweden) synthetically produced a substance that resembled the component smells in wolf urine. The motivating principal behind this development is that all ungulates possess a natural instinctive fear of predators (Koehne 1991). Fraser and Hristienko (1982) demonstrated that putrescent material (putrescent egg and cattle manure) and certain volatile compounds (isobutyric acid and creosote) were effective in repelling moose from salty roadside pools in Ontario. However, some researchers question the long-term utility of scent deterrents because the substances tend to deteriorate over time (Fraser and Hristienko 1982).

Intercept feeding.—In some areas lack of quality forage in roadside forests caused deer to use the right-of-way as a food source (Feldhamer et al. 1986, Waring et al. 1991). Planting unpalatable species within the right-of-way or creating alternate feeding areas away from the roadway can discourage ungulate use of roadside habitat or intercept ungulates moving toward the road. Indeed, Fraser and Thompson (1982) showed that alternative salt sources could be established to lure moose away from the highway. Wood and Wolf (1988) showed intercept feeding of mule deer to be useful at reducing ungulate-vehicle crashes in Utah. They further suggested that intercept feeding might reduce ungulate-vehicle collisions by <50 percent over the short term. However, Wood and Wolfe (1988) do not recommend intercept feeding for long-term reductions as it is labor intensive, and ungulates may become dependent upon supplemental food.

Improve Motorist Ability

Several measures exist that attempt to improve a driver's ability to react should they encounter a large mammal in the roadway (Koehne 1991). By improving the driver's ability to react, both the severity and the frequency of ungulate-vehicle crashes can be reduced (Koehne 1991). Some measures for improving the driver's ability to react have included: (1) reducing vehicle speeds in high crash areas to allow the driver more time to react after spotting an animal; (2) removal of vegetation adjacent to the roadway to allow the driver to see the animal before it enters the roadway; (3) installing additional roadway lighting to improve nighttime visibility; and (4) through signing and public education programs. Mitigation measures included in this category do not restrict or hamper ungulate movements. Instead, these countermeasures attempt to give vehicle drivers an early warning of a large mammal's presence, such that they can increase attentiveness or decrease speed.

Speed reductions.— Early reports on road-killed wildlife implicated increasing traffic speeds as a potential factor in increasing collisions (Stoner 1925, Haugen 1944). Since then, high vehicle speeds have commonly been considered one of the central causes of ungulate-vehicle collisions (Pojar et al. 1975, Case 1978, Groot Bruinderink and Hazebroek 1996). Bashore et al. (1985) found that the probability of white-tailed deer-vehicle collisions decreased with lowered speed limits. Gunther et al. (1996) concluded that vehicle speeds are a primary factor contributing to large mammal-vehicle collisions in Yellowstone National Park. In Yellowstone, large mammal-vehicle collisions occurred more than expected on roads with posted speeds of 88.5 km/h ($P<0.10$) and less than expected on roads with posted speeds of 72.4 km/h or less ($P<0.10$; Gunther et al. 1996). By reducing vehicle speeds through high incident locations, motorists potentially have a greater opportunity to avoid ungulate-vehicle collisions. Lavsund and Sandegren (1991) demonstrated that reduced speed limits at least reduced the severity of moose-vehicle collisions in Sweden. However, white-tailed deer-vehicle accidents increased with increased vehicle speeds only to an asymptote (88 km/h) after which they decreased (Allen and McCullough 1976). Although speed reductions are regarded as a solution among many natural resource agencies, reductions in posted speed have not been thoroughly evaluated with regard to frequency of ungulate-vehicle collisions (Romin and Bissonette 1996).

Although speed is linked to the probability of being in an ungulate-vehicle collision, such events prove to be complex and are seldom attributable to a single factor (see Transportation Research Board 1998). Beside the obvious tradeoff between speed reductions and travel time, other more subtle factors such as speed distribution (range of speed) contribute to collision involvement. Reducing the posted speed below highway design speed has been shown to increase speed distribution and collision rates can be higher on roads with wider ranges of speed (Transportation Research Board 1998). Indeed, slow drivers can be just as dangerous as fast drivers (Transportation Research Board 1998). Although speed reductions are a commonly suggested option to reducing the probability of ungulate-vehicle collisions, such reductions are not ideal from an engineering perspective, and may raise other safety or economic (enforcement) issues. However, increased enforcement may be mitigated through the use of remote video surveillance, which has proven useful in urban environments.

Vegetation removal, Roadside clear-zones.—An important design feature in roadside safety is the provision of an unobstructed space alongside the roadway for errant vehicles to recover and stop without striking a hazard, e.g., trees, power lines, etc. (Ray 1998). Because these unobstructed spaces, referred to as clear-zones, must allow sufficient time for vehicles to recover or stop, appropriate width is determined by the design speed of the roadway and the average daily traffic (ADT). For example, the U.S. Roadside Design Guide recommends a roadside clear-zone of 9 m for roadways with an ADT of 6000 vehicles/day and a design speed of 100 km/h (AASHTO 1996; 3-3). Researchers have suggested that extending the clear-zone out even further improves visibility for motorists and allows a measure of advanced warning, giving the driver a greater scanning area and more time to reduce speed or avoid a crash (Lavsund and Sandegren 1991). For example, Jaren et al. (1991) found that spraying vegetation with the herbicide glyphosate (Roundup®) in a 20- to 30-m section on each side of two railway lines caused a 56 percent (± 16 %) reduction in the number of moose-train collisions. However, vegetation clear-zones also may attract animals to the roadside where early successional vegetation is exposed, and the method is expensive and must be well maintained due to regrowth (Lavsund and Sandegren 1991).

Highway Lighting.—Because the preponderance of ungulate-vehicle collisions occur during hours from sunset to sunrise, Reed and Woodard (1981) thought that installation of roadway lighting would improve motorist visual acuity. They hypothesized that with increased roadside lighting, animals can be more easily sighted prior to entering the roadway, thus reducing the probability of an ungulate-vehicle collision. Reed and Woodard (1981) noted that highway lighting was successful at reducing serious vehicular accidents in urban settings. However increased highway lighting did not affect motorist speeds, deer crossings, or crossings-per-accident ratios in Colorado, and thus was not effective at reducing mule deer-vehicle collisions (Reed and Woodard 1981).

Signage and Public Education.—Conventional warning signs have been widely used to alert both frequent and infrequent motorists of dangers along the roadway (Pojar et al. 1975). Forty of 43 states (93%) surveyed by Romin and Bissonette (1996) used static deer-warning signs. However, static deer-warning signs have been shown to have a limited effect on driver behavior but may be useful for public relations and liability considerations (Pojar et al. 1975). Warning signs could be effective if they required reduced speeds. However, signs are common and do not necessarily predict ungulate presence; thus motorists become complacent to the warning (Romin and Bissonette 1996, Putman 1997). Messmer et al. (1999) shows flashing seasonal warning signs to be effective in reducing motorist speeds on Highway 89 in Utah, but cautions "drivers may initially slow down because of the flashing lights and signs, but if they do not encounter deer, their speeds may increase." Studies have shown that drivers base their behavior on what they see on the road in front of them and not necessarily on the signing (e.g., Aberg 1981). Even seasonally lighted, animated deer-crossing signs failed to elicit enough of a motorist response to reduce the number of mule deer killed attempting to cross State Highway 82 in Colorado (Pojar et al. 1975). Similarly, Lehnert and Bissonette (1997) found a lack of motorist response to crosswalk warning signs and surmised that they may have been mistaken for conventional ungulate-warning signs.

Public education programs inform motorists of potential dangers in the roadway environment. The intent is to alter driving behavior and improve alertness levels. Public awareness programs were used by 22 of 43 states (51%; Romin and Bissonette 1996). Although, 24 percent believed the programs successful (62% inconclusive) these programs have not been rigorously evaluated (Romin and Bissonette 1996). Potential information distributed through a local public education effort should include statistics showing magnitude and severity of the problem, high crash locations, the times at which the risk is highest, what a driver can do to minimize risk, and what a driver should do if a crash does occur. In spite of inconclusive results, educating motorists of the risks of ungulate-vehicle collisions remains a fundamental recommendation of several authors (Pojar et al. 1975, Lavsund and Sandegren 1991, Groot Bruinderink and Hazebroek 1996).

Review of New Mitigation Opportunites

In a search for more sophisticated ways to reduce ungulate-vehicle collisions, transportation agencies have turned to advanced technology solutions, such as animal-detection driver-warning systems (Hughes et al. 1996). Such systems detect large mammal presence on the roadside and provide an active, dynamic warning to the motorist. These systems focus on two aspects of the problem: (1) ability to detect ungulate presence on or approaching the roadway, and (2) the driver's response to dynamic warning signs. Animal detection can be accomplished through a single method or a combination of methods. Currently, vendors are promoting microwave radar, passive and active infrared, fiber-optic grating, seismic sensors, or thermal imaging technologies to detect large mammals. Image recognition software can be used to identify animal presence in video or infrared images. Buried seismic sensors may detect ground vibrations caused by animal presence. A beam may be broken such as microwave radar, laser, or other light-wave sent between a transmitter and a receiver. Microwave radar detection systems have the highest potential for success because the systems are capable of reducing false detections caused by blowing vegetation or other small animal intrusions (Taskula 1997). A disadvantage of complex systems of this type is the need to use advanced software packages, which require the ability to process many algorithms.

Once animals have been detected in the right-of-way, drivers are warned of ungulate presence via dynamic signing, flashing beacons, or audible warnings. Given the limited effectiveness of conventional, static signing to elicit a motorist response, dynamic signing is perceived as more appropriate and can range from a static sign with a flashing beacon to a full matrix variable message sign (Pojar et al. 1975, Cook and Daggett 1995). Recently, several pilot animal-detection, driver-warning systems have been installed, including: (1) Moose Warning System, Finland; (2) FLASH System, Wyoming; (3) Laser Detection System, Washington; and (4) Dynamic Elk Crossing, Washington. We reviewed each of these systems.

Moose Warning System, Uusimaa, Finland

In Finland, moose account for about 1300 collisions annually, costing about $10 million in human injury and property damage (Taskula 1997). In 1995 on all public roads in the Uusimaa region, 435 moose collisions were reported to police. On Highway 7, a moose-detection driver-warning system was installed to increase motorist awareness of the hazard and to alleviate vehicle damage. Here, moose were funneled by 1650 m of fence into a designated 220-m opening that allowed moose to cross the road (Taskula 1997). A motion-detecting system, using microwave radar sensors (two/pole, 50 m apart) spanned the 220-m crossing in the right-of-way. Positive detections triggered fiber-optic moose-warning signs located approximately 150-200 m upstream of the crossing/detection zone on both sides of the road (4 in all). Minor adjustments concerning moose movement rates were necessary to avoid false detections due to blowing grass and small birds (Taskula 1997). To reduce false detections caused by rain and air pressure fluctuations, passive infrared detectors and a rain detector were also built into the system. Driver reaction, in the form of reduced speed, was measured during periods of sign activation using inductive loop traffic detectors. When encountering the activated signs (versus control periods), motorists decreased speed in rainy conditions (14.0-15.6 km/hr) and at night (1.6-2.6 km/hr), yet there was little impact on motorist speed during daylight periods with good visibility (increase of

0.4-0.5 km/hr; Sabik Oy, unpublished report).

FLASH System, Nugget Canyon, Wyoming

On U.S. Highway 30 in Wyoming between Kemmerer and Cokeville, collisions kill hundreds of mule deer annually during seasonal migrations (Gordon and Anderson 2002). The extensive road crossings, along with occasional crossings by elk, pronghorn (*Antilocapra americana*), and moose prompted officials to install 11.3 km of ungulate-proof fencing in 1989 (see Reeve and Anderson 1993) with one opening for ungulate crossings. Additionally, an ungulate-detection driver-warning system was installed at each side of the fence openings. The detection system consisted of two passive infrared radar sensors detecting deer body heat and a backup system of 10 buried geophone sensors detecting ground vibrations caused by ungulates. The infrared detection system coupled with flashing beacons and signing to form the driver-warning system, while the geophone system served as a partial backup and gathered data on crossing frequency. Conventional signing was modified to read "Deer on Road when Lights are Flashing." The infrared system turned the lights on only when an animal is detected in the crossing zone. Additionally, highway advisory radio played a 30-second informative message about the crossing zones and why drivers should reduce speed. Initially, technical issues such as detection zone layout, sensor alignment, and optimal positioning of signs hampered the evaluation of the effectiveness of this system. Researchers found that more than 50 percent of the detections registered by the FLASH system were false detections although the backup geophone system functioned nearly perfect (Gordon and Anderson 2002). Data collected to gauge driver reaction to the system revealed that passenger vehicles and tractor-trailers significantly reduced their speed by 18.7 and 10.1 km/h, respectively, when signs were animated and a mule deer decoy was deployed in the crossing (Gordon and Anderson 2002). Other treatments resulted in decreases in vehicle speeds ≤8 km/hr (<5 mph) that we deemed insufficient to reduce the likelihood of an ungulate-vehicle collision. These results showed that speed reduction was generally higher for passenger cars than tractor-trailers. Very few large trucks responded with any reduction in speed.

Laser Detection System, Colville, Washington

The Washington Department of Transportation identified MP 290 on US Highway 395, south of Colville near Chewelah, Washington, as a high ungulate-vehicle collision area (J. Schafer, Washington Department of Transportation, personal communication). The highway segment is 402 m in length with the necessary clear line-of-sight along the right-of-way to support a simple broken-beam detection system. The system consisted of two lasers (one on each side of the road); two conventional deer warning signs with supplemental plaques, which read "When Flashing" and red beacons. The system was partially solar-powered and activated the warning beacons when the detection beam was broken. Unfortunately, the system experienced numerous technical and maintenance problems. Sighting the laser proved difficult, as proper alignment at threshold distances (400 m for most beam technologies) can be difficult to obtain and sustain. Distortion of the laser via direct solar radiation disrupted sensor alignment and lead to detection failures and false detections without shade hoods. Theft of solar power units also has been a problem.

Dynamic Elk Crossing, Sequim, Washington

On the Olympic Peninsula near the city of Sequim Washington, approximately 10,000 vehicles pass through on Highway 101 per day. From 1994 to 2000 despite standard crossing signing installed in 1996, vehicles killed 12 resident Roosevelt elk (*C. elaphus roosevelti*) whose home range was bisected by the road. Collisions between vehicles and elk presented a safety concern for the region, which likely would increase when the new Sequim Bypass, completed during fall 2000, produced increased traffic volumes and road density. To address the problem, local officials installed an ungulate-detection driver-warning system in December 2001. Eight adults were radio collared from a herd of 81 elk. The VHF signal transmitted from their collars triggered warning signs located along 4.8 km of highway the elk frequently cross to reach the northern portion of their range. The six signs were standard elk crossing signs (with "ELK X-ING" supplemental plaques) modified with flashing beacons. When the collared elk moved within 402 m of the highway right-of-way, the 360-degree whip antenna detected their proximity and the radio-activated signs began flashing to warn motorists to reduce speed. Since installation, one traffic-related elk mortality was documented. The limited data available suggest that the system decreased mortality from 1.7 to 0.5 elk/yr.

Discussion

To date, the problem of large mammal-vehicle collisions has been underestimated (Groot Bruinderink and Hazebroek 1996). Some successes in reducing ungulate-vehicle collisions have been documented with traditional countermeasures such as fencing, modified fencing, and grade separation via crossing structures (Table 2). However, traditional solutions to ungulate-vehicle collisions are often expensive, e.g., fencing, overpasses, have limited effectiveness, e.g., reflectors, static warning signs, or may damage the environment by furthering habitat fragmentation or creating barriers to movement, e.g., ungulate-proof fencing, vegetation clear-zones.

Although there is significant interest and potential in ungulate-detection driver-warning systems, our review of the literature indicated a paucity of clear information on accuracy and reliability for different ungulate detection sensors currently available. Critical parameters that affect feasibility of ungulate-detection driver-warning systems include: detection zone layout, differentiation of large mammals from smaller objects, duration of warning signal, motorist reaction time, and local climatic conditions (Taskula 1997). Other problems include inherent range limitations, coverage limitation within detection zones, and impacts of background influencing animal-detection efficiency. False detections pose a common problem among most of the systems reviewed. One of the leading theories is that multiple detection systems, where two or more detectors must be triggered to verify animal presence, would reduce or eliminate false detections (Taskula 1997). Any dynamic warning system carries substantial development costs; have the potential for considerable maintenance costs, e.g., aligning and replacing sensors, and costs will compound with multiple systems. Until costs are reduced, ungulate-detection driver-warning systems should only be placed in discrete areas of high crash occurrence. Even if detection technologies work flawlessly, motorists may not respond enough to dynamic signing to significantly reduce the probability of ungulate-vehicle collisions (e.g., Gordon and Anderson 2002).

Effective testing of ungulate-vehicle collision mitigation measures has not kept pace with development of alternative methodologies. Many evaluations have been short-term tests of commercially developed and marketed products, e.g., Swareflex reflectors. Evaluations that compared ungulate mortality before and after installation yielded confounded results of efficacy (e.g., Pafko and Kovach 1996) because many studies recognized that the ungulate-vehicle collisions vary temporally with respect to topography, habitat, behavior, local population concentrations, time, and traffic volume. Some early evaluations lacked experimental controls, which precluded robust conclusions about expected collision numbers in the absence of countermeasures (Gilbert 1982). Where experimental controls have been used, they often are merely adjacent roadway sections (e.g. Lehnert and Bissonette 1997). Independence can be compromised by control sections proximity to treatment sections (see Bomford and O'Brien 1990). In such cases, countermeasures in treatment sections may displace ungulates onto control sections, potentially enhancing the treatment's effect. We recommend systematic, well-designed tests of different countermeasures. Emphasis also should be placed on increasing motorist response to animal-detection driver-warning systems. If motorists do not respond by reducing speed or increasing vigilance, the best detection system will be ineffective.

Engineers should consider highway design in an ecological context to reduce interactions between ungulates and vehicles. New road designs and reconstruction plans should include wildlife passage at critical locations. This is fundamental to any attempt to mitigate the problem and may itself require a major effort, as broad scale studies of landscape features contributing to ungulate-vehicle collisions are generally lacking (Hubbard et al. 2000). Finder et al. (1999) demonstrated that deer-vehicle accident statistics, along with remotely sensed habitat and highway data might be used to predict high incidence deer-vehicle collision locations.

An example of the potential for agency cooperation is the improvement of U.S. Highway 93 on the Flathead Reservation from Evaro to Polson (90.6 km) in northwest Montana. Recently, a memorandum of agreement was signed by the Confederated Salish and Kootenai Tribes, Montana Department of Transportation, and Federal Highway Administration allowing for expansion of the highway from 2-lanes to a combination of 2-lanes, 4-lanes, and passing sections. This document further mandated retrofitting the highway with 42 fish and wildlife crossing structures and 23.7 km of ungulate-proof fencing for a total estimated cost of just over $9 million (CSKT et al. 2000).

Although costs of many preventive measures likely are high, benefits resulting from a reduction in accidents to the motoring public and wildlife need to be adequately addressed via cost-benefit analysis (Reed et al. 1982). High mitigation costs may only be justified for major roadways or interstates (Putman 1997). For primary roads that combine high speed and high traffic volumes across important wildlife habitat, the most effective approach to ungulate-vehicle mitigation is to combine barrier fencing with wildlife crossing structures to provide large mammal permeability (Groot Bruinderink and Hazebroek 1996). In instances in which fencing costs or effects are prohibitive, as on secondary roadways, Groot Bruinderink and Hazebroek (1996) recommend animal detection-driver warning systems in which the goal of mitigation may be to delay rather than prevent crossings (Putman 1997). A monitoring program using track counts or infrared detection technologies to assess large mammal use and mitigation efficacy is critical to the long-term success of any management action (Groot Bruinderink and Hazebroek 1996).

Conclusion

Clearly, there is no quick fix to the problem of ungulate-vehicle collisions, but potential solutions do exist. With development of new technologies, acknowledgement by transportation agencies of ecological problems caused by roads, and new funding initiatives such as the Transportation Equity Act for the 21st Century, there is potential for increased implementation of rigorous testing of techniques for reducing ungulate-vehicle collisions. There also is a greater awareness that countermeasures should be applied within the context of a large-scale strategy to reduce problems within road corridors.

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