Integrated adaptive design for wildlife movement under climate change

Nina-Marie Lister[1*], Marta Brocki[1], and Robert Ament[2]

Climate change is anticipated to alter both wildlife movement and distributions. Despite mounting evidence that wildlife-crossing infrastructure offers a reliable, physical solution to the linked problems of wildlife road mortality and habitat fragmentation, pervasive barriers – from economic to governance structures – prevent the widespread introduction of an infrastructure network. To overcome these barriers, and to cope with the challenges posed by climate change, we argue that proactive, anticipatory planning and evidence-based, integrated highway-impact mitigation strategies are needed. Specifically, wildlife-crossing infrastructure should emphasize an integrated and adaptive approach to constructing innovative, modular, and potentially moveable structures that can be transferred from one location to another as monitoring of habitats and wildlife needs indicate. Continued investment in fixed, static structures, which are typically based on engineering standards designed for traffic loads rather than wildlife movement, may prove ineffectual as habitats change in composition and location, potentially leading to associated changes in the locations of wildlife–vehicle collisions.

Front Ecol Environ 2015; 13(9): 493–502, doi:10.1890/150080

Many studies have detailed the ecological impacts of roads, including loss of habitat and landscape connectivity (Trombulak and Frisell 2000), direct animal mortality (Benítez-López *et al.* 2010), demographic impacts to wildlife populations and their genetic consequences (Fahrig and Rytwinski 2009; Sawaya *et al.* 2013, 2014), hydrological disruptions, erosion, sedimentation, exotic invasions, and noise and light pollution (Spellerberg 2002; Crooks and Sanjayan 2006; Beckmann *et al.* 2010). Roads fragment habitats and create barriers that impede wildlife mobility (Forman and Alexander 1998; Forman 2003). In the short term, landscape fragmentation by roads is associated with increasing instances of wildlife–vehicle collisions (WVCs), which put both people and non-human animals at risk; landscape fragmentation can also result in genetic isolation, putting some species of wildlife at risk over the longer term (Trombulak and Frisell 2000; Van der Ree *et al.* 2011).

In a nutshell:

- Roads divide habitats into smaller fragments and prevent wildlife from moving freely across landscapes to breed, feed, and find shelter
- Wildlife crossings – road infrastructure that has proven effective in reducing the impacts of roads by reconnecting landscapes over and under roads – can facilitate the movement of wildlife between areas
- The regions that wildlife species will inhabit are likely to shift as climate changes, but the exact nature of these migrations is difficult to predict, thus necessitating a precautionary and anticipatory approach to increasing connectivity between habitats
- Novel solutions being developed involve the design and construction of adaptive and flexible infrastructure, as well as the removal of systemic barriers to implementation of these new systems
- An integrated approach will allow wildlife managers, researchers, and decision makers to anticipate and respond to wildlife movements in ways that are safe-to-fail and specific to local contexts

More than half a century of continuous road building in North America has resulted in growing numbers of WVCs – including a 50% increase in just the past 15 years – leading to rising levels of personal injury and property damage (Huijser *et al.* 2007). One to two million collisions between cars and large mammals are estimated to occur every year in the US, representing a serious threat to both human safety and wildlife populations (Huijser *et al.* 2009). Transport Canada reports that between four and eight collisions with large animals take place every hour in Canada alone, and that there is an increasing annual trend in reported WVCs with large ungulate species such as deer (*Odocoileus* spp) and moose (*Alces alces*; Vanlaar *et al.* 2012). The Ontario Ministry of Natural Resources records indicate that one in five collisions includes a wild animal (MNR 2008). The risk of collisions involving wildlife is greater during migration seasons and in certain areas – motorists are at an increased risk in the suburban regions of the US and southern Canada, for instance (State Farm Insurance Canada 2011; Vanlaar *et al.* 2012). The proportion of accidents that are caused by WVCs is also increasing over time, costing North Americans more than US$8 billion annually (Huijser *et al.* 2009).

WVCs are also a source of concern for wildlife; road mortality is a major threat to the survival of 21 species listed under the US Endangered Species Act (Huijser *et al.* 2007). Road building also has effects beyond direct

[1]*Urban and Regional Planning, Ryerson University, Toronto, Canada* [*]*(nm.lister@ryerson.ca);* [2]*Road Ecology Program, Western Transportation Institute, Montana State University, Bozeman, MT*

mortality – for example, habitat loss through the linked processes of habitat fragmentation and the consequent habitat restriction as wildlife species are limited to increasingly isolated patches (Trombulak and Frisell 2000; Forman 2003). As wildlife populations become more isolated and less able to move freely to breed and feed, they become susceptible to loss of genetic viability (Forman and Alexander 1998). Habitat fragmentation and associated threats to biodiversity are growing in urbanizing landscapes, which in Canada are southern, temperate landscapes that are home to most of the country's biodiversity, including many threatened and endangered species (MNR 2008).

The rapid and continuous proliferation of roads and vehicle traffic worldwide necessitates a better understanding of their social and ecological impacts. There are over 102 million km of paved and unpaved roads in the world (Table 1), a number that rises each year. North America contains more than 7.5 million km of roads, and has one of the highest rates of automobile ownership of any country: more than a quarter of a billion vehicles use these roads already (Davis *et al.* 2011; CIA 2013). Global passenger and freight travel on roads and rails is predicted to double in the next four decades, creating an additional 25 million km of new roads worldwide (Dulac 2013). Much of this new infrastructure will occur in the world's fastest urbanizing regions – as a response to growth, rather than as a proactive plan – with little concern for the environmental consequences (eg UN 2014; WHO 2014).

As more roads and motorized vehicles encroach farther into the world's natural landscapes and intact ecosystems, efforts must be made to mitigate the continued ecological degradation and loss of biodiversity (Laurance *et al.* 2014). Counteracting the negative impacts of global transportation infrastructure will require a comprehensive and interdisciplinary approach to research, conservation, planning, and education – and specifically, an integrated approach to the design of mitigation strategies. New and improved methods are required that can help to reconcile social and ecological values with the need for safe and efficient movement of goods and services. This has become one of the most pressing contemporary issues affecting human communities and biodiversity

Table 1. Total length of the global road network, top-ranking countries in terms of road length, and other areas of interest around the world (CIA 2013)

Country and global rank	*Total road length (km)*[a]	*Road density (km km^{-2})*	*Roads per capita (km person^{-1})*	*Comments*
(1) US	6 506 204 (4 374 784 paved)	0.7	0.021	Most in North America
(2) China	4 106 387 (3 453 890 paved)	0.4	0.003	Most in Asia
(3) India	3 320 410[b]	1.0	0.003	
(4) Brazil	1 580 964 (212 798 paved)	0.2	0.008	Most in South America
(5) Japan	1 210 251 (973 234 paved)	3.2	0.010	
(6) Canada	1 042 300 (415 600 paved)	0.1	0.030	
Other areas of interest				
Australia	823 217 (356 343 paved)	0.1	0.037	
Germany	644 480 (644 480 paved)	1.8	0.008	Most in Europe; includes local roads
South Africa	362 099 (73 506 paved)	0.3	0.007	Most in Africa
Greenland	0	0.0	0.000	Roads are in towns, not between towns
North America	7 914 599 (4 922 673 paved)	na[c]	na	
EU total	5 814 080[b]	na	na	
World total	102 260 304	0.8[d]	0.15[e]	

Notes: [a]year reported varied by country, from 1999 to 2011; [b]ratio of paved to unpaved roads unknown; [c]na = not available; [d]total world land area was based on information from The World Bank (http://data.worldbank.org/indicator/AG.LND.TOTL.K2); [e]total world population in 2012 based on information from The World Bank (http://wdi.worldbank.org/table/2.1).

across the globe, a challenge that will be compounded by the future effects of climate change.

Wildlife-crossing infrastructure

Maintaining ecological connectivity has become a key focus of efforts to combat these collective threats (Soulé *et al.* 2006; Crooks and Sanjayan 2006; Heller and Zavaleta 2009; Mawdsley *et al.* 2009). As more landscapes are fragmented by roads, it is increasingly difficult to maintain, let alone to restore, habitat connectivity (Clevenger and Wierzchowski 2006). Most of the world's current surface transportation systems were constructed without considering ecological effects or connectivity – and more are on the way. A new systematic and integrated approach is required: one that constructs new, and retrofits old, transportation infrastructure with a specific focus on maintaining permeability for all types of species, large and small. Such an approach also requires adaptability and modularity through innovations in infrastructure design and materials (Brocki *et al.* 2014), and concomitant studies to ensure ongoing monitoring and the implementation of evidence-based best practices (Rytwinski *et al.* 2015).

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Figure 1. *A wildlife overpass in Banff, Canada.*

One recognized solution to improve safety for both humans and wildlife, alleviate habitat fragmentation, and restore wildlife movement is the placement of wildlife-crossing infrastructure at key points along transportation corridors (Clevenger 2005; Crooks and Sanjayan 2006; Clevenger and Barrueto 2014). Wildlife-crossing structures have been successfully introduced throughout Europe and in various locations in Asia, Australia, and North America (Forman 2003; Beckmann *et al.* 2010; Clevenger and Barrueto 2014). Wildlife-crossing structures include both underpasses (culverts, ecopassages, tunnels) and overpasses (bridges), which have been constructed in a variety of sizes and designs and are highly effective (Bekker and Vastenhout 1995; Clevenger and Huijser 2009; reviewed in Glista *et al.* 2009). Although wildlife underpasses are less costly to build and more commonly used by a diversity of species, wildlife overpass structures are preferred by certain wide-roaming and charismatic species-at-risk, such as grizzly bears (*Ursus arctos*; Clevenger and Waltho 2005). Overpass structures are highly visible to passing motorists and, as such, may offer a public education function in communicating conservation advocacy values and the importance of landscape connectivity (Lister 2012). In addition to providing benefits to human and wildlife in the form of increased safety and mobility, crossing infrastructure can serve as a source of important long-term data on wildlife movement and behavior.

Long-term monitoring and research at more than 20 crossing structures in Banff National Park (Figure 1) in Alberta, Canada, and at several European sites, has shown that when designed appropriately for target species and used in tandem with fencing, wildlife-crossing infrastructure can reduce WVCs by more than 90% (Clevenger and Waltho 2000; Clevenger *et al.* 2009). Crossing structures also facilitate effective wildlife mobility over time, as populations become acclimated to the structures and use them to access food, shelter, and breeding partners or grounds (Clevenger *et al.* 2009; Clevenger and Barrueto 2014). Monitoring studies of existing structures have provided evidence that these crossing structures also have longer-term benefits in the form of increased gene flow between some populations (Sawaya *et al.* 2013, 2014).

Barriers to implementation

Despite extensive scientific evidence supporting the efficacy of wildlife-crossing infrastructure (Beckmann *et al.* 2010), implementation in North America has been both slow and sparse. In Canada, where few municipal, provincial, or federal agencies have planning and implementation experience, only in the provinces of British Columbia, Alberta, and Ontario are there a small number of prototype structures. The perceived and real costs of adding these structures have contributed to their limited application and study (Sawaya *et al.* 2013). Yet, WVCs are rarely considered in safety and cost–benefit analyses undertaken by transportation agencies (Table 2). Although the capital investment required would be substantial, the benefits extend over the lifetime of the crossing structure. When considered over the typical 75-year life cycle of an over- or underpass, these benefits effectively solve the problem of road mortality altogether (Table 3). Unlike the costs of reducing bird-strikes by aircraft (which are ongoing and calculated annually) WVCs can be reduced over the entire life of the mitigating infrastructure. For example, installing an overpass along a segment of roadway that has 3.2 deer–vehicle collisions km^{-1}

yr^{-1} would generate economic benefits considerably in excess of its lifetime capital costs, in addition to providing the ecological benefits of improved landscape connectivity and increased permeability (Huijser *et al.* 2009). When use over time is factored into cost–benefit analysis, the benefits more than justify the cost of construction.

Yet these benefits do not appear to be widely understood or valued. Kociolek *et al.* (2014) reported that 84% of surveyed professionals employed by US state-level departments of transportation reported that their agency had considered building a wildlife crossing to improve road safety and landscape connectivity. However, the majority of respondents cited economic reasons (eg lack of funding) as the primary barrier to implementation. In addition, operational and jurisdictional barriers were identified as further major impediments. Notably, there are currently no known examples of agency-led planning and design protocols in place anywhere in North America. Legislative support, coupled with leadership at all levels of government, is clearly needed for the widespread deployment of wildlife crossings.

Parallel technologies

Other measures may also serve to mitigate WVCs, including intelligent vehicle (or collision avoidance) technologies that are being developed to reduce the incidence of driver error, the cause of over 90% of vehicle collisions (NHTSA 2008; Eskandarian 2012). These existing and projected technologies include, for instance, forward collision warning and auto-brake systems; lane departure warning and auto-correction systems; adaptive headlights; blind spot detection; and large-animal detection systems (Forslund and Bjarkefur 2014). Proponents suggest that overall vehicle collisions, including WVCs, could be reduced if human error were mitigated through technological improvements to vehicles, and even more so if vehicles were to become fully autonomous. However, the ability of vehicle technologies to effectively identify small or even medium-sized wildlife is not well documented, as recognition technology is currently being developed only for large mammals (Forslund and Bjarkefur 2014). Road mortality will continue to be a problem for smaller animals, which often make up a large proportion of species identified in roadkill surveys (Huijser *et al.* 2009). Although intelligent vehicle technologies have the potential to reduce WVCs involving some larger-bodied species, they cannot mitigate the effects of landscape fragmentation caused by the extensive and expanding road network itself, a process that affects animal species irrespective of their size.

Climate change and wildlife movement

Along with the projected effects of climate change, habitat fragmentation and loss constitute the greatest threats to biodiversity (Travis 2003), and these negative effects are expected to increase substantially in the future. The changing climate is projected to cause major shifts in the potential ranges of species (Lawler *et al.* 2006) and the ability of species to keep up with these changes is likely to be limited (Davis and Shaw 2001) both by individual species' dispersal ability and by the barriers to movement posed by habitat loss, fragmentation, and physical infrastructure. Regardless of these limitations, climate-change projections suggest that many wildlife species may be forced to migrate in search of new habitats, using different routes and patterns, as resources become scarce in their current home ranges (Heller and Zavaleta 2009). Dense road networks and associated habitat fragmentation will inevitably pose additional barriers for wildlife, substantially affecting global biodiversity.

Evidence from past periods of climate change, contemporary observations, and predictive models provide insights into the effects of changing climate on ecosystems. The paleoecological record shows shifts in species distributions as a result of climate changes dating back to the glacial–interglacial transition (Graham *et al.* 1996; Martínez-Meyer *et al.* 2004; Lister and Stuart 2008). Shifts in species range and dispersal are cited as a primary adaptive response to changing climate conditions (Parmesan and Yohe 2003; Vos *et al.* 2008; Williams *et al.* 2008). Over recent decades, long-term changes in the distribution of flora and fauna have been documented across both terrestrial and marine taxa, and in particular insect and plant taxa (Parmesan and Yohe 2003; Root *et al.* 2003; Heller and Zavaleta 2009), and predictive models anticipate continued effects of rising atmospheric carbon dioxide concentrations (Burns *et al.* 2003). A poleward shift in the northern margins of species ranges, as well as expansion upward along elevation gradients, is commonly observed in response to rising temperatures (Hughes 2000; Walther *et al.* 2002; Parmesan 2006; Chen *et al.* 2011).

Habitat loss and land-cover changes in urbanizing landscapes are projected to further exacerbate the negative effects of

Table 2. Summary of estimated costs (in 2007 US dollars) for the average collision between a vehicle and deer, elk, or moose (Huijser *et al.* 2009)

Cost type	*Deer* (*Odocoileus spp*)	*Elk* (*Cervus canadensis*)	*Moose* (*Alces alces*)
Vehicle repair	$2622	$4550	$5600
Human injury medical	$2702	$5403	$10 807
Human fatality insurance	$1002	$6683	$13 366
Towing, accident attendance, and investigation	$125	$375	$500
Hunting value of animal	$116	$397	$387
Carcass removal and disposal	$50	$75	$100
Total	**$6617**	**$17 483**	**$30 760**

a warming climate and associated ecosystem changes (Mawdsley *et al.* 2009). These impacts include impeding gene flow and increasing genetic isolation, as well as diminishing the ability of species to relocate in order to accommodate geographic changes in resources and preferred climatic conditions (Soulé *et al.* 2006; Vos *et al.* 2008). There are a variety of potential strategies to conserve and protect biodiversity as the effects of climate change on habitats and species ranges become ever-more apparent. In addition to increasing the size of and connectivity between existing protected areas, strategies include the management and restoration of ecosystem functions, translocation of at-risk species, and the enhancement of landscape-level connectivity and permeability for a wide variety of species (Williams *et al.* 2008; Heller and Zavaleta 2009; Lawler 2009; Mawdsley *et al.* 2009). Although species may differ in their ability to move through a corridor (Lawler 2009), many respond positively to landscape-corridor infrastructure (Krosby *et al.* 2010).

In this context, wildlife-crossing infrastructure may have considerable potential to enhance movement corridors and permeability for terrestrial species across roadways (Clevenger 2012; Sawaya *et al.* 2014). However, there is inherent uncertainty in accurately predicting future distributions and movements of wildlife under unprecedented climate scenarios, which complicates site selection for wildlife crossings (Mawdsley *et al.* 2009; Krosby *et al.* 2010). Conventional designs for fixed overpass structures are typically used as the basis for wildlife crossings, but these structures are designed according to engineering standards for vehicle traffic loads rather than for surface habitat creation and wildlife movement (Lister 2012). As such, the engineering standards for conventional overpasses are a constraint to more innovative and flexible design solutions that could otherwise be adapted to changing habitats and conditions. Planning for and investing in conventional structural designs may prove ineffectual as habitats change in composition and location.

Accurately predicting future species movements is further complicated by major differences in anticipated con-

Table 3. Effectiveness and costs of wildlife–vehicle collision mitigation measures for large ungulates

Mitigation measures	*Effectiveness*	*Crossing opportunity?*	*Source*[†]	*Present value costs*	*Costs per percent reduction*
Seasonal wildlife warning sign	26%	Yes	Sullivan *et al.* (2004): 51%; Rogers (2004): 0%	$3728	$143
Vegetation removal	38%	Yes	Jaren *et al.* (1991): 56%; Lavsund and Sandegren (1991): 20%	$16 272	$428
Fence, gap, crosswalk	40%	Yes	Lehnert and Bissonette (1997): 42%, 37%	$300 468	$7512
Population culling	50%	Yes	Review in Huijser *et al.* (2007a)	$94 809	$1896
Relocation	50%	Yes	Review in Huijser *et al.* (2007a)	$391 870	$7837
Anti-fertility treatment	50%	Yes	Review in Huijser *et al.* (2007a)	$2 183 207	$43 664
Fence (including dig barrier)	86%	No	Reed *et al.* (1982): 79%; Ward (1982): 90%; Woods (1990): 94–97%; Clevenger *et al.* (2001): 80%; Dodd *et al.* (2007): 87%	$187 246	$2177
Fence, underpass, jump-out	86%	Yes	Reed *et al.* (1982): 79%; Ward (1982): 90%; Woods (1990): 94–97%; Clevenger *et al.* (2001): 80%; Dodd *et al.*(2007): 87%	$538 273	$6259
Fence, under- and overpass, jump-out	86%	Yes	Reed *et al.* (1982): 79%; Ward (1982): 90%; Woods (1990): 94–97%; Clevenger *et al.* (2001): 80%; Dodd *et al.* (2007): 87%	$719 667	$8368
Animal detection systems (ADS)	87%	Yes	Mosler-Berger and Romer (2003): 82%; Dodd and Gagnon (2008): 91%	$1 099 370	$12 636
Fence gap, ADS	87%	Yes	Mosler-Berger and Romer (2003): 82%; Dodd and Gagnon (2008): 91%	$836 113	$9610
Elevated roadway	100%	Yes	Review in Huijser *et al.* (2007a)	$92 355 498	$923 555
Road tunnel	100%	Yes	Review in Huijser *et al.* (2007a)	$147 954 696	$1 479 547

Notes: "The estimated effectiveness, present value costs (in 2007 US$, 3% discount rate), and costs per percent reduction of mitigation measures aimed at reducing collisions with large ungulates over a 75-year time period. The measures are ordered based on their estimated effectiveness. If a measure is estimated to be 86% effective, it means that ungulate–vehicle collisions are estimated to reduce by 86% as a result of the implementation of that mitigation measure (eg a reduction from 100 collisions to 14 collisions)" (Huijser *et al.* 2009). Table 3 reproduced from Huijser *et al.* (2009). [†]See Huijser *et al.* (2009) for all references cited within Table 3.

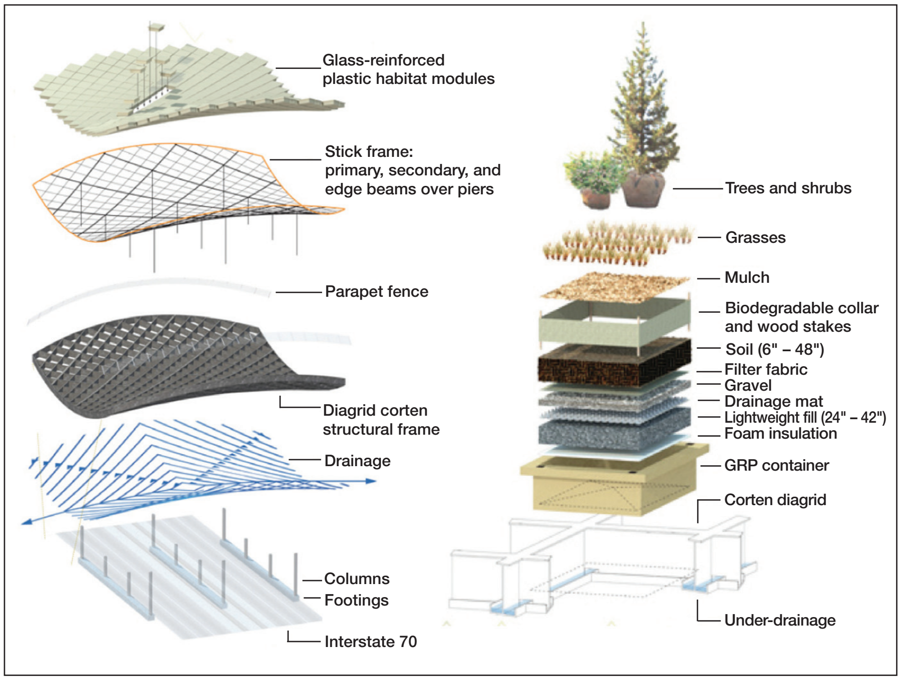

Figure 2. *An innovative and modular wildlife-crossing design. Habitat modules can be reused and adapted to suit present and future ecological conditions (adapted from Olin Studio 2010).*

nectivity needs even for individual species. Species responses to changes in climate are highly variable in terms of patterns and pace, and are to some degree unpredictable due to interacting drivers of ecosystem change coupled with the magnitude and rate of current climate changes (Walther *et al.* 2002; Root *et al.* 2003; Chen *et al.* 2011). Complex and non-linear interactions within ecological communities underline the need to mitigate landscape fragmentation to counteract more than anticipated range changes. Although many of the large terrestrial species prone to road mortality (eg bears [*Ursus* spp], cougars [*Puma concolor*], pronghorn [*Antilocapra americana*], and lynx [*Felis canadensis*]) have large ranges within North America, the preservation of apex predator species can serve as a buffer for climate-change effects by preventing cascading food-chain effects within ecological communities (Sala 2006).

Early calls to action regarding climate mitigation were dominated by the need to reduce atmospheric greenhouse-gas emissions. More recently, mounting evidence of widespread and unanticipated climate-change effects has necessitated a shift in focus and generated political urgency to address practical strategies for the adaptation of human and ecological systems to these unexpected changes. In the face of such uncertainty, a flexible, integrated, and adaptive response to climate change has considerable advantages. Ecologically adaptive wildlife-crossing infrastructure emphasizes one precautionary approach to facilitate responsive, evidence-based action – via feedback gathered through ongoing monitoring – and to mitigate uncertainty associated with predicting changes in habitat composition as well as wildlife needs and movements.

Infrastructural innovation

In 2010, the ARC (Animal Road Crossings) International Wildlife Crossing Infrastructure Design Competition (reviewed in Lister 2012) was launched by a multistakeholder partnership between state and federal agencies and universities, with the goal of exploring new materials, methods, and strategies for wildlife-crossing infrastructure. Motivated by ongoing perceptions that the cost of wildlife crossings were a major barrier to their widespread implementation, the ARC competition challenged respondents to develop structural designs specific to wildlife that would reduce costs, incorporate material innovations, and add value (eg by making more modular or adaptable designs; Lister 2012). In this way, the competition engaged interdisciplinary and international teams of engineers, landscape architects, and ecologists to create the next generation of wildlife-crossing infrastructure for North America's roadways. Design teams were challenged to develop novel solutions for wildlife-crossing structures that would be cost-efficient, ecologically responsive (ie capable of responding to ecological changes through landscape architectural design interventions), safe, and flexible. The finalists developed concept solutions that could be readily adapted for widespread use in different locations under varying conditions – among other innovations, these included stackable, modular components; lightweight resin materials; and interchangeable habitat modules (Figure 2). The ARC competitors also faced the unique challenge of designing an integrated solution for two very different user groups – humans and wildlife – each with different needs and priorities, yet sharing the need for safe passage across roads. The conceptual design solutions that resulted from the competition have been influential in engaging research and building public awareness, if not yet policy, for the planning and design of wildlife-crossing infrastructure (ARC Solutions 2014).

The winning concept design by HNTB Engineering and Michael Van Valkenburgh Associates Inc (landscape architects) offers insights and opportunities for a new class of infrastructure (Lister 2012). Their proposal (Figure 3) for a pillar-free, modular structure makes use of ordinary materials and technology in addition to well-established construction techniques, thereby offering both feasibility and adaptability. The structure employs a three-hinged arch – a hyperbolic parabaloid (hypar) vault – which relies on a pre-cast, thin-shell concrete module designed to safely disperse the energy of an uneven and dynamic load. The concrete modules can be readily fabricated at many pre-casting facilities across the continent, which reduces transportation and construction costs, and the forms can be assembled onsite, resulting in minimal site disturbance (and associated costs). Importantly for climate adaptation, the concrete hypar forms can be readily expanded or adapted onsite if monitoring data suggest a change in wildlife movement or requirements (Figure 4).

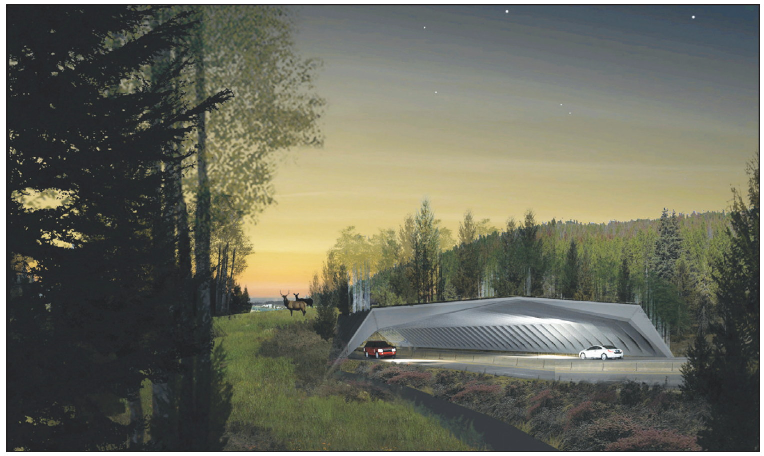

Figure 3. *Stacking two worlds: a pillar-free and modular integrated wildlife overpass design constructed using precast concrete.*

Toward an integrated, adaptive design approach

Despite a growing body of evidence that wildlife-crossing infrastructure is an effective tool for mitigation and adaptation to changing environmental conditions, the innovations developed in both research and design discussed here have been slow to materialize. The problem is a multi-sectoral priority, and is complex, multi-faceted, and growing. More specifically, the costs and risks associated with WVCs are growing, as are threats to wildlife habitat posed by developing urban regions in which road networks are increasingly dense. Changing environmental conditions compound this already complex problem. As such, it is imperative that policy makers, resource managers, ecologists and related scientists, transportation planners, landscape architects, and engineers collaborate formally and proactively to help find effective and creative strategies to design and implement wildlife-crossing structures. While European countries typically have federal or regional planning protocols in place, North American examples are largely ad hoc (IENE 2012; Brocki *et al.* 2014). There is a considerable policy gap in that no single agency in North America is currently responsible for overseeing the planning and construction of such structures, and existing agencies alone clearly cannot provide comprehensive data, planning, design, or policy expertise.

Although cost is an oft-cited barrier to deployment, the more pernicious obstacle to widespread adoption is conventional governance – and in particular, fragmented and locally competitive jurisdictional and institutional arrangements. Although all citizens effectively pay for the social and ecological costs of WVCs and habitat fragmentation, the problem is not in the purview or budget of any one agency and is not addressed in any comprehensive policy framework or planning legislation. Infrastructure-based solutions to habitat fragmentation have demonstrated success, but planning, designing, constructing, deploying, and monitoring these structures must be coordinated, collaborative, and formally integrated. Responsibility for the planning and delivery of this class of infrastructure cuts across scales (urban, regional, and national) and jurisdictions (municipal, state/provincial, regional, and federal). As such, success can be achieved only through an integrated and coordinated multi-sectoral and multi-agency effort – an approach that must also adapt to changing conditions through monitoring and feedback into next-generation practices.

There is a critical need for policy alignment within and between government departments, as well as policy coherence between levels of government, to address complex socioecological problems (Burch *et al.* 2014). Policy-relevant, transdisciplinary, and collaborative approaches that are adaptive and flexible will be required to solve

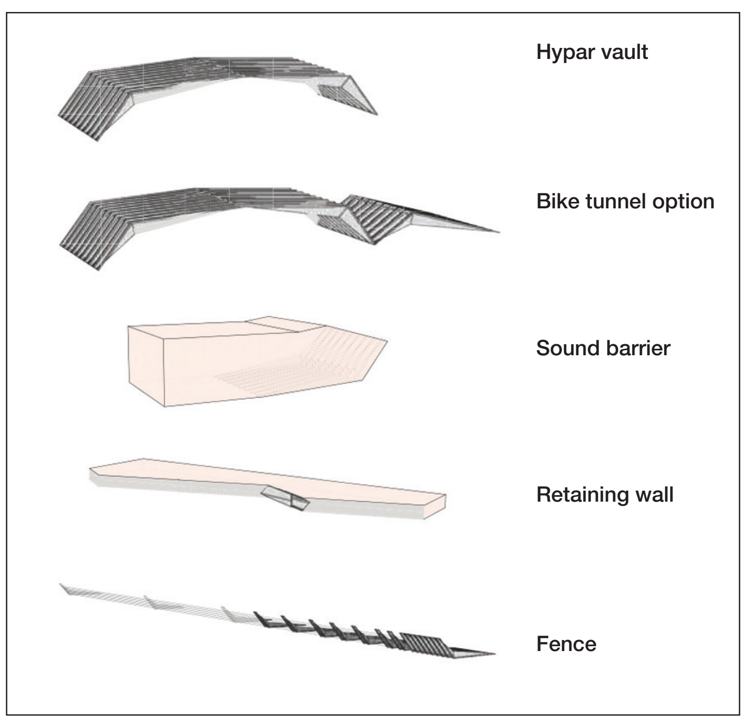

Figure 4. *Individual precast concrete modules can be arranged, adapted, and scaled in response to site context (adapted from HNTB and MVVA 2010).*

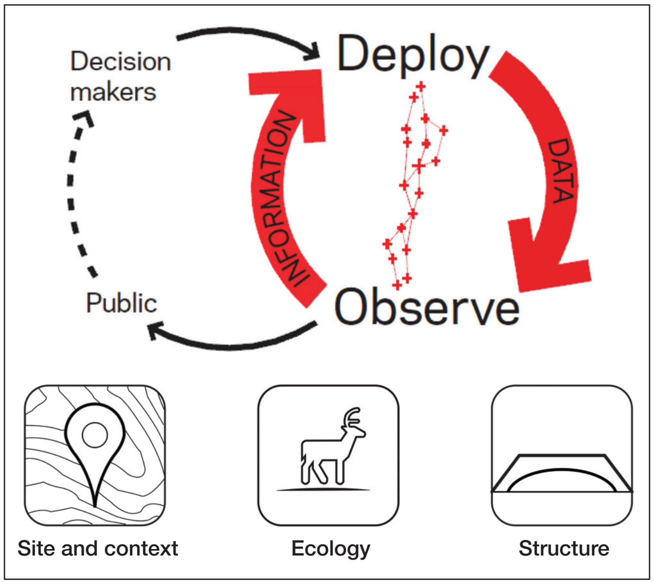

Figure 5. *An integrated design approach is needed for both infrastructure and policy. Infrastructure must adapt to changing conditions through monitoring and feedback; management policies and design practices must be responsive and sensitive to site, context, and local ecology. Image credits: (top) HNTB and MVVA (2010); (bottom) M Brocki.*

such problems, including those associated with habitat fragmentation and especially in the context of unpredictable and unprecedented environmental changes. McGowan and Westley (2014) and others have argued that such "messy" problems can benefit from collaborative design and experiential learning-by-doing to generate transformative learning and to mobilize knowledge (Dale 2001).

We recommend an integrated and adaptive design approach for both a policy framework for planning and implementation, and the physical and programmatic infrastructural design. In addition to coordinating across jurisdictional scales and agencies, policy and planning initiatives for wildlife-crossing infrastructure must explicitly recognize the interdisciplinary nature of the physical infrastructure itself (Figure 5). The structural components of wildlife crossings must necessarily include and affect the engineered superstructure of the overpass (or substructure of the underpass), the roadway, the approach lands on either side of the roadway, and the vegetated landscape surface of the crossing itself. The habitat surface of an overpass is both site- and species-specific and must be designed for target species under local environmental conditions. To be successful, the procurement and commissioning policies for any wildlife-crossing infrastructure must consider all design elements and required components from the outset of the project, including engineered superstructure and landscape architectural habitat design. Without an explicitly integrated approach, these structures are likely to become little more than modified standard bridges with nominal habitat and low- to non-functioning landscape elements.

An integrated design approach must address the policy gap in relation to the implementation of wildlife-crossing infrastructure through the development of a comprehensive planning framework. A key part of this framework will be to develop national datasets of standards in best- and next-practices. With a coordinated and integrated approach to evidence-based design, planning agencies will be better positioned to establish novel methods to design, procure, construct, and relocate adaptive (eg modular), flexible, and innovative structures. In addition, it will be critical to develop and implement shared protocols for monitoring newly deployed infrastructure to ensure continuous learning and to incorporate data and feedback into next-generation designs. This approach must also integrate results into public education programs, as well as the training of relevant professionals and agency participants.

Conclusions

As climate-change effects continue to accrue, wildlife-crossing infrastructure clearly has multiple ecological and social benefits, from reconnecting habitats to creating new, linked habitats, while largely solving the problem of WVCs. But the widespread deployment of this infrastructure necessitates crossing disciplines and boundaries, and is currently hampered by a lack of coherent policy within a formally integrated decision-making framework. Successfully deploying such infrastructure will be possible through integrated and adaptive approaches, supported by political leadership and transparent, full-cost accounting. This initiative also has the potential to connect research with innovative, timely, and context-specific design and policy outcomes – solutions that are urgently needed as wildlife species face increasing threats on our roads.

Acknowledgements

We thank T Clevenger and The Western Transportation Institute at Montana State University for providing leadership in road ecology research and A Harrison at Ryerson University for research assistance. Special thanks to the Woodcock Foundation and ARC Solutions, partners for sustained leadership through seed and leveraged funding for related project initiatives, and to Ryerson University for a partnership development seed grant. Thanks to K Hill for inspiring the title.

References

ARC Solutions. 2014. Design parameters report. Workshop for wildlife-crossing infrastructure. Bozeman, MT: Western Transportation Institute, Montana State University.

Beckmann JP, Clevenger AP, Huijser MP, *et al.* 2010. Safe passages: highways, wildlife, and habitat connectivity. Washington, DC: Island Press.

Bekker H and Vastenhout M. 1995. Natuur over wegen/Nature across motorways. Delft, The Netherlands: Rijkswaterstaat.

Benítez-López A, Alkemade R, and Verweij PA. 2010. The impacts of roads and other infrastructure on mammal and bird populations: a meta-analysis. *Biol Conserv* **143**: 1307–16.

Brocki M, Yuan J, and Lister N-M. 2014. Wildlife crossing design recommendations: innovation in overpass design. Technical report for ARC Solutions. www.arc-solutions.org. Viewed 4 Jul 2015.

Burch S, Shaw A, Dale A, *et al.* 2014. Triggering transformative change: a development path approach to climate response in communities. *Clim Policy* **14**: 467–87.

Burns CE, Johnston KM, and Schmitz OJ. 2003. Global climate change and mammalian species diversity in US national parks. *P Natl Acad Sci USA* **100**: 11474–77.

Chen IC, Hill JK, Ohlemüller R, *et al.* 2011. Rapid range shifts of species associated with high levels of climate warming. *Science* **333**: 1024–26.

CIA (Central Intelligence Agency). 2013. The world factbook 2013–14. Washington, DC: CIA.

Clevenger AP. 2005. Conservation value of wildlife crossings: measures of performance and research directions. *GAIA* **14**: 124–29.

Clevenger AP. 2012. Mitigating continental-scale bottlenecks: how small-scale highway mitigation has large-scale impacts. *Ecol Restor* **30**: 300–07.

Clevenger AP and Barrueto M (Eds). 2014. Trans-Canada highway wildlife and monitoring research. Final report. Part B: research. www.westerntransportationinstitute.org/documents/reports/4W1713_Final_Report_PartB.pdf. Viewed 22 Sep 2015.

Clevenger AP, Ford AT, and Sawaya MA. 2009. Banff wildlife crossings project: integrating science and education in restoring population connectivity across transportation corridors. Final report. http://arc-solutions.org/wp-content/uploads/2012/03/Clevenger-et-al-2009-Banff-wildlife-crossings-project.pdf. Viewed 22 Sep 2015.

Clevenger AP and Huijser MP. 2009. Handbook for design and evaluation of wildlife crossing structures in North America. Washington, DC: Department of Transportation, Federal Highway Administration.

Clevenger AP and Waltho N. 2000. Factors influencing the effectiveness of wildlife underpasses in Banff National Park, Alberta, Canada. *Conserv Biol* **14**: 47–56.

Clevenger AP and Waltho N. 2005. Performance indices to identify attributes of highway crossing structures facilitating movement of large mammals. *Biol Conserv* **121**: 453–64.

Clevenger AP and Wierzchowski J. 2006. Maintaining and restoring connectivity in landscapes fragmented by roads. In: Crooks KR and Sanjayan M (Eds). Connectivity conservation. Cambridge, UK: Cambridge University Press.

Crooks KR and Sanjayan M (Eds). 2006. Connectivity conservation. Cambridge, UK: Cambridge University Press.

Dale A. 2001. At the edge: sustainable development in the 21st century. Vancouver, Canada: University of British Columbia Press.

Davis SC, Diegel SW, and Boundy RG. 2011. Table 3.5: Vehicles per thousand people in other countries, 2002 and 2012. In: Transportation energy data book: edition 30. Washington, DC: US Department of Energy.

Davis MB and Shaw RG. 2001. Range shifts and adaptive responses to Quaternary climate change. *Science* **272**: 673–79.

Dulac J. 2013. Global land transport infrastructure requirements: estimating road and railway infrastructure capacity and costs to 2050. Paris, France: IEA Publications.

Eskandarian A. 2012. Introduction to intelligent vehicles. In: Eskandarian A (Ed). Handbook of intelligent vehicles. London, UK: Springer London.

Fahrig L and Rytwinski T. 2009. Effects of roads on animal abundance: an empirical review and synthesis. *Ecol Soc* **14**: 21–41.

Forman RTT. 2003. Road ecology: science and solutions. Washington, DC: Island Press.

Forman RTT and Alexander LE. 1998. Roads and their major ecological effects. *Annu Rev Ecol Evol S* **29**: 207–31.

Forslund D and Bjarkefur J. 2014. Night vision animal detection. Intelligent Vehicles Symposium IV; 8–11 Jun 2014; Dearborn, MI. IEEE.

Glista DJ, DeVault TL, and DeWoody JA. 2009. A review of mitigation measures for reducing wildlife mortality on roadways. *Landscape Urban Plan* **91**: 1–7.

Graham RW, Lundelius Jr EL, Graham MA, *et al.* 1996. Spatial response of mammals to late Quaternary environmental fluctuations. *Science* **272**: 1601–06.

Heller NE and Zavaleta ES. 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biol Conserv* **142**: 14–32.

HNTB and MVVA (HNTB Engineering and Michael Van Valkenburgh Associates Inc). 2010. ARC International Wildlife Crossing Infrastructure Design Competition. Available at arc-solutions.org.

Hughes L. 2000. Biological consequences of global warming: is the signal already apparent? *Trends Ecol Evol* **15**: 56–61.

Huijser MP, McGowen P, Fuller J, *et al.* 2007. Wildlife–vehicle collision reduction study: report to Congress. Washington, DC: US Department of Transportation, Federal Highway Administration.

Huijser MP, Duffield JW, Clevenger AP, *et al.* 2009. Cost–benefit analyses of mitigation measures aimed at reducing collisions with large ungulates in the United States and Canada: a decision support tool. *Ecol Soc* **14**: 15–41.

IENE (Infra Eco Network Europe). 2012. Safeguarding ecological functions across transport infrastructure. Proceedings of the IENE International Conference; 21–24 Oct 2012; Berlin-Potsdam, Germany. Berlin, Germany: Swedish Biodiversity Centre.

Kociolek AV, Ament RJ, Callahan AR, *et al.* 2014. Wildlife crossings: the new norm for transportation planning. *ITE J* **4**: 45–47.

Krosby M, Tewksbury J, Haddad NM, *et al.* 2010. Ecological connectivity for a changing climate. *Conserv Biol* **24**: 1686–89.

Laurance WF, Gopalasamy RC, Sloan S, *et al.* 2014. A global strategy for road building. *Nature* **514**: 229–32.

Lawler JJ, White D, Neilson RP, *et al.* 2006. Predicting climate-induced range shifts: model differences and model reliability. *Glob Change Biol* **12**: 1568–84.

Lawler JJ. 2009. Climate change adaptation strategies for resource management and conservation planning. *Ann NY Acad Sci* **1162**: 79–98.

Lister AM and Stuart AJ. 2008. The impact of climate change on large mammal distribution and extinction: evidence from the last glacial/interglacial transition. *C R Geosci* **340**: 615–20.

Lister N-M. 2012. Crossing the road, raising the bar: the ARC International Design Competition. *Ecol Restor* **30**: 335–40.

Martínez-Meyer E, Townsend Peterson A, and Hargrove WW. 2004. Ecological niches as stable distributional constraints on mammal species, with implications for Pleistocene extinctions and climate change projections for biodiversity. *Global Ecol Biogeogr* **13**: 305–14.

Mawdsley JR, O'Malley E, and Ojima DS. 2009. A review of climate change adaptation strategies for wildlife management and biodiversity conservation. *Conserv Biol* **23**: 1080–89.

McGowan K and Westley F. 2014. Design thinking, wicked problems, messy plans. In: Reed C and Lister N-M (Eds). Projective ecologies. Cambridge, MA, and New York, NY: Harvard University and ACTAR.

MNR (Ministry of Natural Resources). 2008. Strategy for preventing and managing human–wildlife conflicts in Ontario. Toronto, Canada: Queen's Printer for Ontario.

NHTSA (National Highway Traffic Safety Administration). 2008. National motor vehicle crash causation survey: report to Congress. Washington, DC: US Department of Transportation. www-nrd.nhtsa.dot.gov/Pubs/811059.PDF. Viewed 5 Jul 2015.

Olin Studio. 2010. ARC International Wildlife Crossing Infrastructure Design Competition. Available at arc-solutions.org.

Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. *Annu Rev Ecol Evol S* **37**: 637–69.

Parmesan C and Yohe G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**: 37–42.

Root TL, Price JT, Hall KR, *et al.* 2003. Fingerprints of global warming on wild animals and plants. *Nature* **421**: 57–60.

Rytwinski T, van der Ree R, Cunnington GM, *et al.* 2015. Experimental study designs to improve the evaluation of road mitigation measures for wildlife. *J Environ Manage* **154**: 48–64.

Sala E. 2006. Top predators provide insurance against climate change. *Trends Ecol Evol* **21**: 479–80.

Sawaya MA, Clevenger AP, and Kalinowski ST. 2013. Demographic connectivity for ursid populations at wildlife crossing structures in Banff National Park. *Conserv Biol* **27**: 721–30.

Sawaya MA, Kalinowski ST, and Clevenger AP. 2014. Genetic connectivity for two bear species at wildlife crossing. *P R Soc B* **281**: 20131705.

Soulé ME, Mackey BG, Recher HF, *et al.* 2006. The role of connectivity in Australian conservation. *Pac Conserv Biol* **10**: 266–79.

Spellerberg IF. 2002. Ecological effects of roads. Enfield, NH: Science Publishers.

State Farm Insurance Canada. 2011. Watch out for roadside wildlife: State Farm data shows increased risk in autumn and spring collisions with deer and moose (Ontario News Bulletin).

Travis JMJ. 2003. Climate change and habitat destruction: a deadly anthropogenic cocktail. *P R Soc B* **270**: 467–73.

Trombulak SC and Frisell CA. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conserv Biol* **14**: 18–30.

UN (United Nations). 2014. World urbanization prospects: 2014 revision. New York, NY: UN. http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf. Viewed 8 Mar 2015.

Van der Ree R, Jaeger JAG, van der Grift E, *et al.* 2011. Effects of roads and traffic on wildlife populations and landscape function. *Ecol Soc* **16**: 48–57.

Vanlaar WGM, Gunson KE, Brown SW, *et al.* 2012. Wildlife vehicle collisions in Canada: a review of the literature and a compendium of existing data sources. Ottawa, Canada: Traffic Injury Research Foundation.

Vos CC, Berry P, Opdam P, *et al.* 2008. Adapting landscapes to climate change: examples of climate-proof ecosystem networks and priority adaptation zones. *J Appl Ecol* **45**: 1722–31.

Walther GR, Post E, Convey P, *et al.* 2002. Ecological responses to recent climate change. *Nature* **416**: 389–95.

WHO (World Health Organization). 2014. Global health observatory: urban population growth. Geneva, Switzerland: WHO. www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en. Viewed 5 Jul 2015.

Williams SE, Shoo LP, Isaac JL, *et al.* 2008. Towards an integrated framework for assessing the vulnerability of species to climate change. *PLoS Biol* **6**: 2621–26.