Cost-benefit analyses for wildlife and traffic safety

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Executive summary

In this report, we review selected mitigation measures with respect to their cost, effectiveness and applicability in a mitigation plan. We discuss difficulties in estimating the value of wildlife-vehicle collisions (WVC), i.e. the benefits that can be gained from preventing WVC, and illustrate how they can be related to the costs for mitigation. This is exemplified in a cost-benefit analysis of a Swedish example. Based on these findings, we propose a strategy for mitigation planning together with a checklist that can be used when cost-benefit analyses for wildlife mitigation are to be conducted. We also identify obstacles and challenges that should be addressed to allow for a more comprehensive and effective mitigation of WVC.

Wildlife-vehicle collisions, especially with ungulates such as wild boar (*Sus scrofa*), roe deer (*Capreolus capreolus*), moose (*Alces alces*) and other deer (*Cervus, Dama, Rangifer*), are increasing in many European countries, resulting from the recovery and growth of ungulate populations as well as from the increase in vehicular traffic and expansion of road networks. Attempts to counteract WVC have hitherto not produced convincing effects on a large scale, although road mitigation measures have become common in most countries. It is not certain, however, that appropriate or sufficient mitigation has been employed.

Various measures to prevent WVC have been proposed over the years, many have been installed, some have been evaluated, but only very few have produced a noticeable effect. In order to develop cost-effective measures against WVC, one must understand the factors that cause these accidents in the first place, identify possibilities of changing these factors and clarify responsibilities for implementing the changes.

Clearly, there is no single magic tool that prevents WVC; instead prevention needs a combination of approaches that target different factors on different scales. Road administrations are best skilled to address local factors through an inclusive fencing system. Landowners, private or public, may deal with broader factors related to landscape composition, habitat and animal abundance. The general public, transportation companies and the automobile industry can accomplish changes at global level, i.e. affect transport conditions and driver behaviour in general. These approaches are no substitutes for each other, but rather complement each other in a joint strategy to reduce WVC. The question therefore is not so much what kind of mitigation provides the greatest effect per invested cent, but rather whether mitigation is at all economically beneficial and politically defendable.

The hitherto most effective but also the most expensive approach to prevent WVC is to physically and permanently separate wildlife and traffic. Research clearly advocates an inclusive fencing system consisting of fences that are adapted in height, strength and mesh-size to the behaviour of the target species; escape facilities such as jump-outs; gates or wildlife grids that secure openings in the fence where other roads connect; warning systems and/or animal detection systems that alert drivers approaching the end of a fenced road; and safe passages provided by bridges/tunnels or crosswalks.

A well-designed inclusive fencing system may prevent over 90% of WVC, but, since costs are high, such systems can only be worthwhile when the expected benefits balance the invested costs. This balance does not necessarily imply a positive net value as policy objectives or legal requirements may allow for a certain net cost to occur. Favourable conditions for inclusive fencing systems exist mainly in two different settings: a) on major transportation corridors (where there is political incentive to permanently isolate vehicle traffic from the biological and human environment) and b) on road sections with especially high

accident frequencies, i.e., hotspots in WVC (where there is likely an economic benefit to be gained from mitigation). Studies show that WVC hotspots may contain a substantial proportion of all WVC in a country or region while comprising only a small fraction of the road network. Thus, with relatively few but well-targeted mitigation efforts, WVC can likely be significantly reduced. That this has not already been accomplished is probably due to the fact that traffic safety measures have been prioritised to reduce the risk of human fatalities rather than to diminish the number of accidents per se.

The remaining part of WVC, however (and this may still imply the majority of all cases) is likely more dispersed and occurs at lower frequencies than what is required to outweigh the investment costs. Thus, to mitigate these accidents, less expensive approaches are needed that operate on a larger or global scale and that thereby involve other actors and responsibilities, especially the driver. As a rule of thumb, such approaches should have a better cost-effectiveness as exclusion fences (about €4,500 and be applicable at a length of several kilometres.

At present, repellents, reflectors or scaring devices are not effective in keeping wildlife off roads. Speed reductions, on the other hand, are likely very effective in preventing not only WVC but also other accidents, but since the prolonged travel time has a high price, there is no economic benefit to be gained. Active driver warnings triggered by animal detection systems alongside the road my prove cost-effective, but need further technical and methodological development before they can be evaluated properly. In-car driver assistance systems that may detect bodies near the road and automatically slow down the vehicle may provide a potentially important tool in the future. Evidence-based risk prediction models that communicate with a car navigator or a smartphone have been proposed to issue warnings that are specific in time and place and can educate drivers to increase awareness under certain critical conditions.

This all requires better empirical data on WVC frequencies, continued research on causal factors and on the distributional pattern of WVC, good experimental studies with innovative mitigation approaches and, above all, open collaboration between involved or interested actors.

In order to identify where and whether mitigation is advisable, cost-benefit analyses (CBA) may be employed. They provide a standard methodology used by the transport sector in decisions on traffic safety investments or road design. CBA has, however, important limitations that must be recognised and addressed when applied to WVC. A fundamental problem is that CBA assumes that all costs and benefits are considered and can be expressed in a monetary form. This assumption is of course regularly violated because many of the ecological, ethical and societal benefits cannot be monetised and are thus without weight in the calculation. By default, CBA are hence biased towards a greater reluctance to invest in mitigation because potential benefits are always underestimated. There are ways to compensate for this bias, for example by using CBA merely as a ranking tool in reference to policy targets, but such targets must first be developed for wildlife and WVC.

Another problem is that mitigation measures have a certain economic life length and that both future costs and future benefits must be assessed in a CBA. This may introduce large uncertainties, especially concerning the development of wildlife populations and thus of benefits that may be gained from reduced WVC. There are further sources of uncertainty, for example linked to the quality and representativeness of WVC data. As not all collisions with wildlife are known, existing statistics must be corrected upwards to compensate for the unreported incidents. This correction may need to distinguish between accident types as human injuries are more likely to be reported than damages to property only.

A third challenge is estimating the expected effect of mitigation measures on WVC. Monitoring studies indicate a substantial variability in the performance of individual measures. This may be caused by environmental factors or by differences in the design, but since empirical data is still limited, expected performances may need to be generalised, extrapolated, or simply guessed.

To account for such uncertainties and to test their influence on the final outcome, CBA should preferably explore different parameter ranges, confidence intervals, or even employ simulation models that quantify the relative power of the different uncertainties. The final outcome of a CBA, i.e., the net present ratio of benefits and costs, is thus not a single value, but rather a probability function with an unknown (variable) distribution and mean.

Nevertheless, CBA analyses reported in literature already indicate that there is considerable economic benefit to be gained from mitigating WVC – even with the rather crude estimates and generalisations that have been available so far. It is possible therefore that, with better estimates and more thorough predictions for the expected benefits, many more mitigation proposals may prove to be cost-effective.

In many situations, however, especially when only smaller species are considered, present mitigation approaches to prevent WVC may not appear economically convincing. This calls for both an adjustment in environmental (wildlife) policy and a development of innovative, more cost-effective methods.

To conclude, we recommend that road administrations engage in a dialogue with other stakeholders in society to develop a joint strategy for reducing WVC. Such a strategy will help to identify where further empirical research is needed, how existing data can be used or improved and how responsibilities can be shared to develop and implement efficient approaches. Since the technical and ecological issues are not confined to national borders, we advise initiating coordinated international studies and experiments on mitigation alternatives.

1 Introduction

There is a growing concern about wildlife-vehicle collisions (WVC) in Europe as the number of accidents with wild animals is steadily rising (Bruinderink and Hazebroek, 1996; Borer and Fry, 2003; Putman et al., 2004). Road agencies are searching for more cost-effective solutions, but legal instruments, policy and economic incitement may not be sufficient to motivate mitigation.

One problem is that the socioeconomic costs are most likely underestimated, partly because empirical data is limited and statistics incomplete and partly because most non-consumptive ecological and societal values associated with wildlife cannot be monetised and are thus not considered in standard cost-benefit calculations. In fact, accidents with wildlife may be treated in the same way as accidents with rocks or road signs, and mitigation against WVC is thus perceived as an expensive environmental add-on to road design.

Another problem is the strong focus in traffic-safety policy on preventing human injury and death. As the majority of WVC produces damages to the vehicle only, they are thus ignored from a traffic safety point of view. Mitigation against WVC has thus been primarily planned to reduce consequences for the humans involved, and not to reduce the overall risk of WVC.

With better knowledge about the benefits of mitigation against WVC and a clear policy on reducing WVC as a societal problem, it will be easier to accomplish effective mitigation. This will even have a positive spill-over effect on biodiversity at large as many other species may benefit from measures employed for larger wildlife.

In this report, we discuss and illustrate why road mitigation for wildlife can be economically defendable and which measures may serve most cost-efficiently to reduce animal-vehicle collisions at present. We also identify obstacles and challenges that should be addressed to allow for a more comprehensive and effective mitigation of WVC and propose a simple strategy for mitigation planning. We pay special attention to ungulates because they produce the majority of all quantifiable costs to traffic safety and are typically the focus of mitigation efforts.

2 Wildlife-vehicle collisions

Vehicle collisions with larger wildlife (WVC), especially with ungulates such as wild boar (*Sus scrofa*), roe deer (*Capreolus capreolus*), moose (*Alces alces*) and other deer species (*Cervus, Dama, Rangifer*), are increasing in many countries (Putman et al., 2004; Langbein et al., 2010). These trends are usually a result of the recovery and growth of ungulate populations as well as of the increase in vehicular traffic and expansion of road networks (Skölving et al., 1987; Bruinderink and Hazebroek, 1996; Seiler, 2004; Apollonio et al., 2010; Sullivan, 2011; Massei et al., 2015). Attempts to limit the increase of WVC at national levels have hitherto not produced convincing effects, although road mitigation measures have become common in many countries, especially in Europe and the US (Trocmé et al., 2003; Putman et al., 2004; Van der Grift et al., 2012).

Wildlife-vehicle collisions result from a complex interplay of environmental, behavioural and technical factors (Seiler, 2003; Litvaitis and Tash, 2008) that fall under the responsibilities of:

i. the infrastructure owner (road agencies, transport administrations) – responsible for factors related to road design, traffic volume, speed limit and verge management; factors operate mostly on a local scale;
ii. the landowner (private land owner, companies, municipalities) – responsible for factors that influence the abundance, movements and behaviour of wildlife; factors operate on local to landscape scales;
iii. the transport user (drivers, companies, general public) – responsible for factors that determine awareness, reaction time, vehicle technology, knowledge; factors that operate mostly on a global scale.

Mitigating landscape and global factors requires involving different stakeholders and the public: Landowners and forestry companies may be able to gradually establish a green infrastructure that directs animal movements away from roads (Finder et al., 1999; Hubbard et al., 2000; Malo et al., 2004; Seiler, 2005; Gunson et al., 2011); hunting associations may agree to control wildlife population sizes through increased culling (Ingemarson et al., 2007); automobile industries are developing intelligent driver assistance systems that help detect obstacles on the road and avoid collisions (e.g., the BMW's night vision technology or Volvo's Animal Detection System); and drivers may be alerted with better and more precise information on wildlife-collision risks (e.g., via information campaigns or in-car warning systems). Global mitigation measures likely produce a diffuse effect on WVC that may be difficult to monitor and evaluate. Nevertheless, they are an important contribution to a wildlife mitigation strategy, and it is very possible that technological development in, for example, driver assistance systems will provide a significant tool to prevent collisions in the future.

Road agencies are more focused on mitigation approaches that address local factors related to the road and its immediate surroundings. By tradition, these technical measures can be installed in the infrastructure on site, including wildlife warning signs, speed limits, exclusion fences, crossing structures, animal detection systems, or specific road-verge management routines, etc. (Iuell et al., 2003; Beckmann et al., 2010; Huijser and McGowen, 2010; Langbein et al., 2010). So far, these local measures have produced the most efficient and long-term reliable solutions to preventing accidents with wildlife: fences that keep animals away from traffic and lead them towards bridges and tunnels that provide a safe passage for animals across infrastructure barriers (Clevenger et al., 2001; Hallstrom et al., 2008; Beckmann et al., 2010; Huijser et al., 2015b; Van der Grift, 2016).

Other local mitigation approaches can be partially effective in reducing accident risks, although they may not be able to replace fences and bridges. Examples include vegetation control in roadsides favouring non-palatable species that do not attract wildlife (e.g., (Rea, 2003; Rea et al., 2010; Sivertsen et al., 2010; Meisingset et al., 2014a); forest clearance and de-branching in adjacent forest habitats to help drivers detect animals (Johansson, 1987; Jaren et al., 1991; Jägerbrand, 2012); or supplemental feeding or placing salt-lick stones at a distance from busy roads (Jolicoer and Crête, 1994; Andreassen et al., 2005; Grosman et al., 2009; Grosman et al., 2011). Also, temporary speed limitations, road closure and traffic calming are mitigation options that deserve further evaluation (Seiler, 2005; Jaarsma et al., 2007; van Langevelde and Jaarsma, 2009).

However, fences and bridges are expensive and cannot be installed everywhere unless accident frequencies are especially high or the risk of human injuries is elevated due to, for example, high speed limits and high traffic volumes. Such high-risk road sections, ‘hotspots’ or ‘blackspots’ can be inferred from accident statistics (Ramp et al., 2005; Montella, 2010; Shilling and Waetjen, 2015; Bíl et al., 2016), but caution is required in interpreting the pattern (Elvik, 1997). New statistical methods have been proposed to identify significant clusters in accident distributions at which mitigation can be targeted (Bíl et al., 2013; Bíl et al., 2016). Studies of wildlife-vehicle collisions in Sweden and in Spain reveal that such clusters occupy but a small fraction (about 1%) of the public road network but contain about 20% to 45% of the recorded accidents with different ungulate species (Seiler et al., 2015b; Torellas, 2015; Seiler et al., 2016b). Accident frequencies in these clusters were about 10 times higher than in the rest of the road network. However, whether these clusters also produce the highest costs in terms of human injuries has not yet been studied.

Nevertheless, even if all clusters were mitigated, the majority of all WVC (55%-80%) remains unaffected. These accidents are rather randomly dispersed and thus less easily targeted by conventional mitigation measures. Here lies the true challenge to WVC mitigation efforts. New approaches are needed that either address landscape and global factors (Seiler et al., 2015b) or provide much cheaper alternatives to fences or bridges. For example, wildlife warning systems that alert drivers when animals approach the road at specified crosswalks may provide economical alternatives to bridges or tunnels if traffic volumes are not too high and vehicle speed can be locally and temporarily reduced (Lehnert and Bissonette, 1997; Huijser and McGowen, 2003; Huijser et al., 2015b). Driver education tools are another promising development that provide the means to both collect and visualise accident information (Olson et al., 2014; Viltolycksrådet, 2014; Shilling et al., 2015); they can use statistical analyses of accident statistics to inform drivers on-board when they enter a known (or predicted) high-risk road. Commercial interests in intelligent driver assistance systems (mentioned above) fuel another very powerful technological development that could substantially reduce collision risks with at least larger mammals.

In addition to measures that aim at affecting drivers and driving behaviour, various technical means to influence the behaviour of wildlife have been promoted by public media and advertised for commercial interests. These tools include deer whistles, alarm sounds, scaring devices, lights, reflectors, olfactory repellents, etc. However, with a few exceptions, most of these innovative approaches have failed to produce any significant effect on WVC that would bear up to scientific scrutiny (Van der Grift et al., 2016). More research with a sound experimental design is needed to unveil possible effects and separate mitigation myths from operative tools.

In practice, this leaves road managers with only a very few reliable and expensive measures to mitigate wildlife-vehicle collisions: i.e., fencing systems that prevent animals from entering the roadway and leading animals towards safe crossing opportunities. Barriers and passages should be considered parts of a mitigation package as both require each other. Additional measures such as speed limitations, warning signs, etc. may be see as an add-on to this package, and their main purpose is to increase the efficacy of the package as a whole (Table 1).

The question is therefore not so much what kind of mitigation provides the greatest effect per invested penny, but rather whether mitigation is economically and politically defendable and how much mitigation is needed to achieve the desired effect. Given that mitigation measures are expensive investments in infrastructure, their costs must be balanced by the benefits gained from reducing accidents and maintaining connectivity. How these benefits are measured, in monetary terms (e.g., reduced costs to society) or as the quality of an effect or outcome (e.g., animal and human lives saved), has implications on the decisions made. Both ways have their advantages and limitations.

3 Road mitigation options, costs and efficacies

A variety of different mitigation approaches to prevent vehicle collisions with ungulates has been tested over the past decades, but only very few are apparently effective in reducing accident numbers (see reviews in Keller et al., 2003; Putman et al., 2004; Huijser et al., 2008a; Langbein et al., 2010; Ooms, 2010; Van der Grift et al., 2012; Van der Grift, 2016).

Mitigation approaches can be grouped in relation to responsibility, scale, target or objective (Seiler, 2003; Litvaitis and Tash, 2008)(Table 1). Rather than being a mere theoretical exercise, this grouping may help to underline that an effective mitigation of WVC cannot be achieved solely by road administrations, but instead requires a combination of approaches operating at different levels that necessarily involves different stakeholders. As initially described, road administrations are mostly confined to measures linked to or installed in infrastructure facilities that operate on a local scale. They are thus best equipped to target high-risk roads in particular. Municipalities, private landowners and hunters can influence the overall living conditions for wildlife in the landscape and consequently change the abundance of animals and their movements. This will likely affect WVC risks at several roads simultaneously, that is at the road network level. Individual drivers will be influenced in their driving behaviour through their knowledge and understanding of WVC risks at both general and particular locations. This knowledge can be obtained through information campaigns, driver education, personal experience or immediate warning on site. If this knowledge is insufficient or ineffective, driver assistance systems developed by the automobile industry may help drivers avoid collisions irrespectively of where and when. In other words, these approaches should not be seen as substitutes or alternatives that can be compared in a CEA, but they should rather be used as supplements that can be combined in different ways to provide the most cost-effective mitigation.

In the following, we focus on three major mitigation approaches and their respective components that are available to road administrations and that have hitherto produced a documented effect on WVC (Clevenger et al., 2001; Hallstrom et al., 2008; Beckmann et al., 2010; Huijser et al., 2015b; Van der Grift, 2016).

The approaches are:

i. **Exclusion fencing** – to keep animals off the road and lead them to safe passages;
   a. Fence attributes: different fence qualities, heights and mesh sizes may be needed for different species.
   b. Escape options: jump-outs, one-way gates, etc. will allow animals to leave the fenced road corridor if they accidently get trapped inside.
   c. Fence openings: self-closing gates and wildlife grids will prevent animals from entering through gaps in the fence while allowing people and traffic to connect to the fenced road.

ii. **Wildlife passages** – to provide a safe passage across the road barrier;
   a. Crossing structures: grade separated over- or underpasses that are adapted to wildlife requirements or especially designed for wildlife.
   b. Crosswalks: fence openings that allow for road crossings at grade, designed for larger mammals and secured by driver-warning and animal-detection systems.

iii. **Driver awareness** – to reduce response time and braking distance to avoid collisions;
   a. Active warnings on site with speed limitations and/or animal detection systems or with GPS-triggered in-car warning.
   b. Passive warnings with temporary or permanent speed limits and/or warning signs.

c. Vegetation control in roadsides to increase wildlife being detectable and less attracted to the road verge.

Table 1. Overview of complementary mitigation measures against WVC.

Objective	Responsibility	Scale	Target	Mitigation approach	Function	Pro's	Con's	Overall judgement
to separate animals and traffic	Transport Administration and Road Agency	road, local	animal	fence	to keep animals off the road and lead them to safe passages	highly efficient if done and designed appropriately	expensive, risk of malfunction, barrier effects, requires add-ons	*most advisable if combined with crossing facilities*
to separate animals and traffic	Transport Administration and Road Agency	road, local	animal	repellents	to repel animals from approaching the road	presumably cheap	no proven effect	*not advisable*
to separate animals and traffic	Transport Administration and Road Agency	road, local	animal	reflectors, acoustic signals	to warn or scare animals when cars approach	presumably cheap, teaching effect on animals	inconclusive evidence	*not advisable yet, further research required*
to separate animals and traffic	Transport Administration and Road Agency	road, local	animal & driver	verge management	to reduce attractiveness of road verge, increase detectability	possible positive side effects on overall traffic safety	requires frequent maintenance, inconclusive data	*partially applicable, further research needed*
to separate animals and traffic	Transport Administration and Road Agency	road, local	driver	speed reduction to 50 km/h	to increase driver response time	overall benefit to traffic safety, reduced barrier effects	increased travel time produces high costs	*highly advisable if temporary*
to separate animals and traffic	Transport Administration and Road Agency	road, local	driver	traffic calming / rerouting	to reduce occasions for collisions	reduced overall impact on wildlife, fewer barrier effects	limited applicability, only dislocates problem	*applicable with restrictions*
to separate animals and traffic	Landowner, Hunters, Municipality	landscape	animal	population control	to reduce the abundance of animals near the road	on a large scale presumably effective	ineffective on a small scale, loss of wildlife and ecological values	*only advisable on a large scale*
to separate animals and traffic	Landowner, Hunters, Municipality	landscape	animal	habitat management	to reduce the abundance of animals near the road	presumably long-lasting effects	possible effect on land use productivity, sensitive to changes in land use, untested	*further research needed*
to separate animals and traffic	Driver, Companies, Public	global + local	driver	education	to increase risk awareness and influence driving behaviour	general spin-off on traffic safety	individuality in responses, low overall effectiveness	*further research and technical development needed*
to separate animals and traffic	Driver, Companies, Public	global + local	driver	active in-car warning	to inform drivers when they enter a high-risk road section during high-risk times	evidence-based, concrete and relevant information	individuality in responses, yet untested	*further research and development needed*
to separate animals and traffic	Driver, Companies, Public	global + local	driver	driver assistance systems	to assist drivers in detecting animals and braking in time	in-car solutions, reliable, likely a future standard anyway	yet untested for WVC, presumably not sufficient in high-speed travel	*further research and development needed*
to maintain animal mobility	Transport Administration and Road Agency	road, local	driver	local speed reduction to 50 km/h	to increase driver response time and reduce accident risks	overall benefit to traffic safety, reduced barrier effects	increased travel time produces high costs	*conflicts with transport policy, further research needed*
to maintain animal mobility	Transport Administration and Road Agency	road, local	animal	gap in fence with static speed reduction	to funnel movements to safer crossing places and separate animals from traffic in time	cheap, simple	requires speed cameras, risk of accidents if speed limit not obeyed	*advisable, further research needed*
to maintain animal mobility	Transport Administration and Road Agency	road, local	animal	crossing structures	to separate animals from traffic permanently	high efficacy if done well, multi-purpose use, long-term effect	expensive if built only for wildlife	*most advisable, existing standards may be optimised*
to maintain animal mobility	Transport Administration and Road Agency	road, local	animal & driver	crosswalk with animal detection and driver warning	to funnel movements to safer crossing places and separate animals from traffic in time	proven efficacy, very limited effect on traffic	technically sensitive, applicable to smaller roads only	*highly advisable, further research needed*
to maintain animal mobility	Landowner, Hunters, Municipality	landscape	animal	habitat management, Green Infrastructure	to divert animal movements parallel to or away from the road to safe crossing locations	presumably long-lasting effects	possible effect on land use productivity, sensitive to changes in land use, untested	*further research needed*
to maintain animal mobility	Landowner, Hunters, Municipality	landscape	animal	supplemental feeding, salt, water, etc	to reduce the animals' need or motivation to move across the road	presumably long-lasting effects	possible effect on land use, inconclusive empirical data	*further research needed*

3.1 Driver awareness and wildlife warnings

To inform drivers about accident risks or to influence driving behaviour in order to reduce risks seem to be the most natural approaches to increasing traffic safety. Better-informed drivers who know about the factors that can lead to accidents with wildlife may be more observant and cautious when driving in areas where WVC are frequent. Thus, many countries engage in driver education programmes and information campaigns to increase awareness (e.g., Romin and Bissonette, 1996; Knapp et al., 2004). In Sweden, for example, the National Council for Wildlife Accidents (NVR; www.viltolycka.se), several insurance companies and the public media hold annual campaigns in late summer to warn drivers about the autumn peak in WVC. Special information is distributed to beginners during driver education classes. In addition, since 2010 drivers have been legally obliged to report any traffic incident with ungulates and large carnivores to the police. There is thus much information and enough incentive to be extra attentive when driving during peak-risk hours and in high-risk areas.

However, since these actions operate on a global level and have only a diffuse and very large-scale effect, if any, on WVC numbers, they typically evade statistical evaluation. Large-scale changes in WVC over time may be influenced by many different factors (climate, weather conditions, animal populations, traffic volume, driving speed, etc.) and not be attributable to information campaigns alone, since it is difficult to isolate the effect of information from all other large-scale factors. Although a few studies have been done in Sweden, for example, there are no encouraging results (Almkvist et al., 1980; Ekström, 1980). Even hunters, who should have special knowledge about wildlife, report no fewer accidents with animals than do non-hunters (Seiler et al., 2004; Seiler et al., 2014). Overall, driver information has not yet proven to be effective in mitigating WVC at large (Knapp et al., 2004; Gibby and Clewell, 2006; Huijser et al., 2008b; Elvik et al., 2009). Almkvist et al. (1980) suggest that drivers may not able to stay alert long enough to look for animals along roadsides. If, however, awareness could be focused on a few short road sections, the effect on traffic safety is likely to be high.

Similar arguments apply to permanent wildlife warning signs (Putman et al., 2004; Huijser et al., 2008b; Elvik et al., 2009). Even though signs are normally placed where WVC have occurred frequently or risks are expected to be high, only a few drivers will likely encounter wildlife, while most will never see animals after they have passed a warning sign. It is inevitable that drivers will become used to signs and start to ignore them unless their information is reinforced and actualised by additional warning, such as blinking lights, extra information texts, or, in fact, animals (Elvik et al., 2009). In an experimental study, Sullivan et al. (2004) showed that warning signs with red flags and flashing beacons reduced WVC by 51% during the first year after the signs were installed. But even by the second year, responses decreased as drivers presumably got used to the signs.

Thus, wildlife-warning signs should be active only during high-risk times and only at specific locations as in animal-activated crosswalks (see below). An alternative to road installations may be provided by in-car warning systems that use the actual time, GPS location and speed of the vehicle and relate this to risks predicted from empirical correlation studies of WVC. When risks exceed predefined levels, specific warnings could be issued by the driver's smart phone, the car's navigation system or future intelligent in-car safety technology. Such software tools appear promising, especially since much of the road and traffic information that is still provided by physical signs may be given only digitally in the future and vehicles will thus be equipped with all the necessary hardware. Yet, further research is needed to evaluate the potential of this approach.

3.2 Speed limitation

Another and very efficient way to increase traffic safety in general is by imposing speed limitations. High speeds and great variations in speed produce increased risks of accidents and human injuries because the demands on the driver's attentiveness and reaction increase with speed and because the braking distance increases proportionally with the square of the speed (Elvik et al., 2009). According to the so-called 'power model' (Elvik et al., 2004; Elvik, 2009), a speed reduction of 1% reduces the risk of human injures on average by the power of about 2.2. The risk of fatal injuries even decreases by the fourth power of the change in speed to which a body is exposed in an accident. The risk of property-damage-only accidents declines by the power of 1.5 (95% confidence limits: 0.1, 2.9).

Thus, a reduction from 90 to 50 km/h could reduce human fatalities and injuries by about 73% (65%-78%) and the number of other non-injury accidents by about 58% (95% C.I.: 5.7 – 82%) on average. Provided that merely 1% of all WVC lead to human injuries, one may thus expect a reduction in WVC of about 59%. After studying statistics on moose-vehicle collisions, Seiler (2005) found that the effect of reducing speed from 90 to 50 km/h on roads with traffic volumes of 8,000 ADT might reduce the risk of accidents with moose by about 50%. The effect on collision risks with roe deer was not studied but is presumed to be similar.

Imagine an unfenced, rural road with 8,000 vehicles per day and an operational speed limit of 90 km/h. Assume further that an average of 2.3 WVC per km and year are reported at a mean cost of €6,500 per incident. Reducing speed from 90 to 50 km/h along one 1-km section of this road might reduce WVC by up to 60% according to the 'power model'. During a 15-year period (recommended life length of traffic safety mitigation measures; Swedish-Transport-Administration, 2016b), this would produce a savings of €179,400 in WVC costs (see Table 2). To this should be added positive side effects such as reducing non-wildlife accidents, fuel consumption, CO^2 emission, or noise pollution.

However, a speed reduction of this magnitude, i.e. below the operational speed of the road, is controversial and may indeed not be effective unless limitations are enforced through physical or visible installations. Not all drivers are likely to respect unmotivated speed limits, and instead the variation among actual driving speeds may increase as one group of drivers will obey speed limitations and the other group will continue at original or operational speeds. Consequently, this increases the risk of accidents without and maybe even with wildlife (Huijser et al., 2008b; Elvik et al., 2009).

In addition, reducing speed also increases travel time, and travel time is valued very highly in socioeconomic calculations. According to the Swedish Transport Administration (Swedish-Transport-Administration, 2016c), car travel time for mixed 90% leisure and 10% professional trips on rural roads is rated at 116 SEK or about €12 per person and hour (at price levels for 2014). A permanent speed reduction from 90 to 50 km/h at a traffic volume of 8000 vehicles per day as in the above example would increase total travel time by about 25,956 hours annually, producing a socioeconomic cost of €311,467 per year. Multiplied over the project's economic life length of 15 years and including an annual increase in traffic of about 2% during these years, the total travel time costs would rise to over 6 million euros.

Thus, addressing WVC by reducing traffic speed permanently and on a larger scale is obviously not economically defendable. However, if speed limitations are employed only locally (i.e. at a 100m-wide crosswalk) and for very evident reasons and are triggered by animal-detection systems only during those times when animals are actually near the road (which may not be more than 1% of the entire year), costs of increased travel times are minimised (about €600 per year, including maintenance of the crosswalk; see Table 2).

3.3 Exclusion fences

Wildlife fences are the most common and reportedly most successful measure to prevent animals from entering the roadway (van der Ree et al., 2015) (Clevenger et al., 2001; Glista et al., 2009; Huijser et al., 2015a). Fences for ungulates are usually of wire-mesh (10-15 cm in mesh size) and often 2 m or more in height (to account for larger ungulates). Other fence types (barb-wire, electrified wires) have been tested but found less effective, hazardous to other species or not competitive in cost-effectiveness compared to wire-mesh fences (Almkvist, 1976; Almkvist, 1978; Almkvist et al., 1978; Huijser et al., 2008b; Stull et al., 2011; Huijser et al., 2015a). Many countries have developed technical standards for the type and material of fences and fence posts as well as best-practise guidelines for the appropriate construction of fences with regard to distance to the road, fence locations on embankments, their connection to bridge abutments and other facilities that terminate fences (Keller et al., 2003; Cueto et al., 2011; Swedish-Transport-Administration, 2014; Huijser et al., 2015a).

Clearly, an effective fence design must be adjusted to the target species and their abilities to climb, jump, dig or force their way through an obstacle (van der Ree et al., 2015). Fence bases may need to be buried or anchored in the ground to prevent the uplifting or tunnelling made by wild boar, for example, or badgers (Iuell et al., 2003). Fences and fence posts must be sufficiently robust to bear the weight of larger deer and of ice and snow without breaking or bending (Swedish-Transport-Administration, 2012a). Fence material must also be strong enough to prevent animals from being trapped or injured when running into a fence. Some fences may need to be complemented with overhanging lashes or floppy tops to prevent climbing animals or must be combined with narrow-mesh fences in their lower part to extend protection to smaller animals as well (Figure 1, Figure 2). Fences are often combined with gates (that allow access roads to connect with the fenced road while preventing animals from entering), with self-closing doors (for humans to leave the roadway) and with electric barriers (i.e., rubber sections) or special groundings to counteract induction effects from high-power lines or electrified railroads near the fence.

Exclusion fences are expensive investments that require annual maintenance and frequent repairs. According to the Swedish Transport Administration (Swedish-Transport-Administration, 2016d), traditional moose fencing is budgeted at about €40,000 – €50,000 per km road (with fences on both sides). Fences also targeted for wild boar, with buried or anchored bases and finer mesh-sizes, are budgeted at €50,000 – €60,000 per km road. To this must be added the price for gates, doors and for any adjustments in the fence design to ensure tight connections to over- and underpasses. If the topography is hilly or even mountainous or the road crosses over many watercourses, fence installation may be additionally demanding. Thus price estimates can vary substantially from case to case. In our model, we assume an average cost of €50,000 with a variability of 20% (€10,000) per km road depending on design characteristics.

Figure 1. Left: Traditional moose exclusion fences in southern Sweden combined with a fine-meshed lower fence to prevent accidents with wild boar. Photo: Andreas Seiler. Right: Wild boar family benefitting from a hole in a fence. Photo: Mattias Olsson.

Figure 2. Road exclusion fences and an experimental one-way gate for sika deer (Cervus nippon) in 2005 in the Shiretoko National Park in Hokkaido, Japan. Note the brown colouring and the conifer plantation to aesthetically mask the fence from the side of the road. Photo: Fumihiro Hara.

Empirical data clearly indicates that exclusion fencing can reduce collision numbers by over 80% in larger ungulate species and somewhat less in smaller species (Bellis and Graves, 1971; Falk et al., 1978; André, 1979; Skölving, 1979; Almkvist et al., 1980; Ward, 1982; Bashore et al., 1985; Feldhamer et al., 1986; Nilsson, 1987; Wiberg and Meirik, 1987; Clevenger et al., 2001). Nevertheless, there are also studies reporting little or no effect, especially when fences are short and fence endings unsecured (Feldhamer et al., 1986; Väre, 1995; Clevenger et al., 2001; Gulsby et al., 2011; Huijser et al., 2016). But very long contiguous fences may also become less effective since animals, especially migratory species, may force their way through the fences if they do not find appropriate passages (Seiler et al., 2003; Helldin et al., 2007). In addition, a recent analysis of ungulate-vehicle collisions in Sweden identified blackspots in accidents even on fenced roads (Seiler et al., 2016b). Clearly, fence efficacy results from several factors such as design, material, length, location and not least construction and maintenance (Huijser et al., 2015a). Critical to safety are any kind of fence gaps, openings or endings where animals may inadvertently or intentionally enter the road corridor. Once an animal has entered the roadway, it may likely be trapped between the fences on either side and not able to find an exit. Consequently, the risk of accidents with panicked animals and probably also the severity of the possible injuries to the driver will be increased. In fact, vehicle speeds on fenced roads are often slightly increased compared to unfenced roads where drivers are more aware of the risk of colliding with wildlife. However, increased speed quickly increases the risk and severity of other, non-wildlife accidents (Elvik et al., 2009). The overall resulting effect on traffic safety and the socioeconomic benefit from fencing may thus be considerably smaller than if only wildlife accidents are concerned. Further research is needed to evaluate this risk.

The Norwegian handbook on traffic safety (Elvik et al., 2009) recommends assuming that fences alone do not increase local traffic safety by more than 55%. When using a landscape or regional approach, overall efficacy should be regarded as even smaller (25%). However, if fences are combined with jump-outs or exit ramps and with sufficient appropriate wildlife passages, the efficacy of such an inclusive fence system will be increased to over 80%.

3.4 Escape ramps, jump outs and one-way gates

Fences are never entirely safe; animals will always find accidental holes or benefit from openings and gates through which they can enter the fenced road corridor. These may be rare events and therefore very difficult to study empirically, but the risk of severe accidents is presumably high enough to justify the provision of specific exit opportunities for wildlife to leave the corridor even when in panic or in stress.

Thus, as part in an inclusive fence system, exit opportunities such as jump-outs, escape ramps or one-way gates have been recommended for many years (Reed et al., 1974), and studies from the US suggest a very high cost-effectiveness (Bissonette and Hammer, 2000; Dodd et al., 2007; Huijser et al., 2009; Siemers et al., 2013). Yet, uncertainties over details in design and placement have so far impeded their implementation in Europe (Iuell et al., 2003).

Jump-outs or escape ramps are rather simple constructions that require very little initial investment and maintenance (Figure 3). When new roads are constructed, the soil construction required to mount escape ramps is likely negligible. But on existing roads, especially when concrete fundaments need to be installed to establish the necessary height differences that hinder animals from jumping into the fenced corridor, costs may reach up to €10,000 per site (Olsson, 2009).

Figure 3. Upper picture: jump-out in southern Sweden (Photo: Mattias Olsson). Lower picture: escape ramp seen from the roadside in Arizona, USA (Photo: Andreas Seiler).

Figure 4. Left: experimental one-way gate for moose and roe deer in Sweden (Photo: Mats Lindquist). Right: experimental one-way gate for sika deer in Hokkaido, Japan (Photo: Andreas Seiler). Efficacy of both gate types is unknown. Due to the risk of failure, one-way gates are no longer recommended.

One-way gates (Figure 4) are more controversial and more prone to technical and material problems (Bissonette and Hammer, 2000; Huijser et al., 2008b). Gates may get stuck in snow or growing vegetation, and door-blades or wings may break under the pressure of animals or snow, leaving a potential gap in the fence through which animals can enter (Sielecki, 2007). Also, animals may learn how to enter the gate from the wrong side (Reed et al., 1974; Lehnert et al., 1996). Due to the risk of failure in gate systems, it is generally recommended to use ramps or jump-outs instead of any technical-mechanical device (Huijser et al., 2008b).

Exit opportunities need to be installed on both sides of the road and preferably not further than about 100 m from the nearest possible entrance (Olsson, 2009). The exact position must be decided by taking into account the terrain and vegetation.

3.5 Fence openings and gaps

Fences along roads are necessarily interrupted wherever other roads or paths connect with the road and humans or vehicles need to exit the fenced road. These opening should be secured to prevent animals from entering the road corridor. Several prevention methods have been tested, but as with jump-out and one-way gates, the empirical evidence is scarce and not conclusive. Cattle grids (Figure 5) are a common phenomenon in many European countries, but most are not optimised for wild ungulates. In the US, wildlife grids have been developed and tested with promising results, achieving efficiencies of 50-89% in ungulates (Allen et al., 2013). Costs of installing wildlife grids can vary substantially with design and requirements on the grid base. Huijser et al (2008) calculate that an average installation cost about €30,000. Problems are known to occur during winter with ice and snow, but further technical development is being conducted. It is likely that future grids can be installed for a much lower price.

Gates, on the other hand, are a simpler and more commonly used solution, especially in Nordic countries where they allow access to rarely used forest roads. Their main advantages are the low price of as little as €3,000 per gate (Huijser et al., 2008b; Seiler and Olsson, 2015) and the fact that, if properly installed and closed, they are as efficient as a fence in inhibiting animal movements. However, gates or gates that are left open clearly imply a safety risk. Another drawback is that gates are not feasible on access roads with more regular traffic. Here, wildlife grids may still be useful.

If the busier roads connect to the fenced road, neither grids nor gates can be installed. Instead, fences are often extended along the connecting roads for some 20 – 50 m depending on the surrounding habitat and terrain. These extensions lead animals that follow the fenced road away from the intersection. The problem, however, is that deer can learn to utilise these openings to cross the fenced road at the intersection. This behaviour has been observed in radio-collared fallow deer in Sweden (Petter Kjellander, SLU, unpublished). Not surprisingly then that accidents with wildlife along otherwise fenced roads seem to aggregate at road intersections and other fence gaps ((Seiler et al., 2016b). Fence openings for connecting roads could be secured with the help of animal-detection systems that alert drivers when animals approach the opening (see below).

Figure 5. Cattle/wildlife grid over a private road connecting with a highway near Osby, southern Sweden. Efficacy in preventing moose or deer from entering the road is unknown. Photo: Mattias Olsson.

There is limited knowledge about the effect of grids, gates or fence extensions on collision risks with wildlife. It is obvious that they are significantly better than unprotected gaps, although they are still only partially effective (Peterson et al., 2003; Huijser et al., 2008b). Further research is needed to develop a fully satisfying solution. We consider them as integrated components of the fencing system, necessary for the fence to achieve its full effect.

3.6 Fence endings

A similarly critical factor for the functioning of exclusion fences is the way in which fences are terminated (van der Ree et al., 2015). Studies on wildlife-vehicle collisions indicate that accident frequencies are often increased at fence endings (Puglisi et al., 1974; Feldhamer et al., 1986; Clevenger et al., 2001; van der Ree et al., 2015). So far, no optimal solution for open fence endings has been proposed, but several approaches have been implemented. Optimally, fences should lead animals to feasible and safe crossing structures, but where this is not possible, fences may need to be extended into areas where the risk of collisions is presumably reduced (Swedish-Transport-Administration, 2012a). This may include areas that are less suitable for or attractive to the target species and thus repel animals from approaching the fence ending; or areas of good visibility for drivers so that they have a better chance of detecting wildlife near the road (Figure 6). Also, drivers must be warned before they approach a fence ending either from within or outside of the fenced section. This can be done by passive warning signs (as is the standard), but preferably by active warning systems that also detect the presence of animals and then impose a temporary speed reduction and warning signal in much the same way as can be done in levelled wildlife crossing structures (Huijser and McGowen, 2003; Huijser et al., 2015b).

Figure 6. Fence ending with standard wildlife warning sign and information text that fences terminate in 200 m. Photo: Andreas Seiler.

A remaining problem is that animals may enter the fenced road corridor at fence endings. Solutions developed for minor connecting roads (gates, grids) are not applicable on larger, busier roads, and fences cannot be drawn too close to the driving lane because of safety reasons. There are ongoing tests with electrified mats that can be integrated into the concrete or asphalt without affecting road surface behaviour (van der Ree et al., 2015). In summary, fence endings are critical factors that need to be addressed more in research and monitoring. Maladapted and unsecured endings are an obvious traffic hazard and can weaken the overall mitigation effect of fences. Effective securing of fence endings will only partially reduce accident risks, but never entirely prevent collisions with wildlife – unless fences are well connected to safe passages.

As with escape ramps or gates and fence openings, secured fence endings should be considered as an integrated component of the inclusive fencing system, not as deliberate add-ons. In some cases it may therefore be more economic to extend fencing until an existing potential crossing structure can be reached instead of investing in advanced technical solutions (active warning systems) to secure shorter fences.

3.7 Crosswalks – level crossings

Crosswalks imply a relative small (<100 m) gap in the fence through which animals are able to enter – and hopefully cross – the roadway (Figure 7). Similar to fence endings or openings for other (minor) roads, crosswalks require effective systems to i) detect wildlife approaching the opening and ii) alert drivers when animals are present (Romer and Mosler-Berger, 2003; Strein et al., 2008; Huijser et al., 2015b). They also require that animals are able to respond to traffic and/or that drivers are willing to avoid colliding with animals that enter the roadway. Thus, crosswalks typically target ungulates and other large mammals. Different solutions have been tested to detect wildlife near roads, including thermal cameras, motion sensors, radar and electro-magnetic fields (Huijser and McGowen, 2003; Strein et al., 2008; Huijser et al., 2015b); technical development is progressing fast, producing more reliable and less expensive systems. These systems trigger the warning system that alerts drivers and, preferably, imposes a temporary speed reduction. Warning drivers and inducing the appropriate response, i.e. increased attentiveness and reduced driving speed, is a critical task (Nowakowski et al., 2013) that may require mandatory speed limitations and control by speed cameras. Without active driver alerts or enforced speed regulations, drivers are unlikely to reduce their speed and the risk of accidents with crossing wildlife will be unaffected (Lehnert and Bissonette, 1997). However, secured crosswalks that combine animal detection systems with effective driver alerts can achieve very high efficacies (33-97%) in reducing accidents with wildlife (Huijser et al., 2015b).

The costs of crosswalks vary depending on the details in detection systems and warning systems. Estimates are about €50,000 per unit (including warning signs, speed limits, fence integration and power supply). It is very likely that prices for installation and maintenance will drop considerably in the future as the systems will be produced in greater quantities. Crosswalks are attractive and cost-effective measures to provide safer passages for large wildlife. They may, in fact, be a substitute for bridges or tunnels, however with important limitations:

1. Crosswalks are only feasible on single-lane roads with intermediate to low traffic volumes where operative speed limitations can be temporarily reduced. If traffic is too busy or vehicle speed too high, sudden changes in speed limits, as when wildlife is detected, can lead to rear-end collisions. Also, busy roads may repel animals from approaching the road in the first place (Seiler et al., 2016a). Motorways or highways with multiple lanes and central barriers must be mitigated by bridges and tunnels that physically separate animals and vehicles.
2. Crosswalks are not appropriate for smaller species that cannot detect and respond to vehicles, that are too slow to utilise the gap between passing vehicles or that drivers cannot avoid hitting (Lima et al., 2015; Jacobson et al., 2016). Thus, snakes, amphibians and small mammals may not benefit from crosswalks at all. Also here, a physical separation by means of tunnels or culverts may provide the only possible alternative.

Figure 7. Crosswalk with an animal detection system and a deer warning unit in Aglasterhausen, Germany. Source: Strein et al. (2008).

3.8 Crossing structures – bridges and tunnels

Bridges and tunnels provide the ultimate solution that allows animals to safely cross over busy roads and railroads (Iuell et al., 2003). Various types and adaptations of these crossing structures have been studied, and empirical evidence firmly suggests that both over- and underpasses can be effective in reducing the risk of animal-vehicle collisions and in maintaining ecological connectivity across road barriers (Beckmann et al., 2010). Such crossing structures may be especially designed for wildlife (e.g. ecoducts, green bridges, badger pipes, amphibian tunnels) or primarily built for other purposes but nevertheless suitable or retrofitted to meet the minimum requirements for animals (bridges over private roads, rivers, valleys, etc.). Conventional road bridges may indeed be frequently used by wildlife if they are open enough, placed well and not disturbed by too much vehicle or human traffic (Smith et al., 2015). Studies suggest that passage width and length are crucial factors that determine how likely animals, especially ungulates, will make use of a crossing structure (Rodriguez et al., 1997; Clevenger and Waltho, 2000; Mata et al., 2009; Seiler and Olsson, 2009; Seiler et al., 2015a). Passage height in underpasses appears to be of lesser importance – as long as it is sufficient for the animal to fit through, i.e. not less than 2-3 m for deer (Seiler et al., 2015a). Passages more than 20 m wide are very likely to enable even the largest ungulates to pass through. Smaller species and especially carnivores are considerably less demanding with regard to passage dimensions (Seiler and Olsson, 2009), but they may instead have greater requirements for surface and cover options within the passage (Pfister et al., 1998; Iuell et al., 2003; Mata et al., 2005). This has a practical implication because when new passages are designed or retrofitted into existing roads, passage height and length may have already been determined by other technical limitations. Passage width, on the other hand, can be adjusted more easily to satisfy the safety demands rooted in the biology of ungulates and other species. Changes in passage width are mostly an economic challenge and not so much a practical problem.

How efficient a bridge or a tunnel may be in providing a safe passage to wildlife does not necessarily translate into the efficacy in reducing the risk of accidents. It is possible that even sub-optimal structures may suffice in providing a passage to those highly motivated animals that otherwise would attempt breaching the fence and cause a traffic hazard (but see Seiler et al., 2003). In other words, even smaller passages that are not efficient in providing passage may be sufficient to reduce WVC. A Swedish study suggests that both the density of conventional bridges and their openness (width-length ratio) affect WVC numbers on roads (Alves, 2011). We recommend more research on the traffic safety effects of crossing structures – especially of conventional and retrofitted bridges.

A combination of exclusion fences with a well-designed and sufficiently large wildlife passages may reduce WVC by more than 90% (Huijser et al., 2008b). Without fencing, passages may still be effective at the very location of the bridge, but may be of little benefit to animals approaching the road next to the bridge unless high traffic volumes repel animals from approaching the road. Clearly, fences with a wildlife bridge or even an ecoduct provide the ultimate tool to reduce WVC and provide connectivity to a wide range of species and ecosystem processes. Investment costs are, however, substantial. Costs will vary with bridge design, substrate, location and current market prices, but for a given type, costs typically increase linearly with the surface of the bridge, i.e., the product of bridge width and length. The Swedish Transport Administration recommends a standard rate of up to €2,000 per square meter bridge surface to estimate the overall investment cost for new bridges (Swedish-Transport-Administration, 2012b). This produces a total cost of about 2.4 million euro for a 20 m-wide passage spanning across a 60 m-wide highway. The cost is significant and, even if an economic life length of over 40 years is considered (compared to a 15-year life length in fences), bridges are unlikely to be cost-effective when benefits are calculated solely with respect to reduced wildlife-vehicle collisions as done in Table 2.

Figure 8. Conventional bridges over a private forestry road (above) and in combination with an extended wildlife passage (below). Both bridges provide a potential passage to wildlife and have been monitored using sand beds (Seiler and Olsson, 2009). Due to its small size, the upper passage is significantly less effective in providing connectivity to wildlife than the larger passage below. Yet, it may nevertheless be sufficient to support the movements of those individuals that otherwise might attempt to breach the fence along the road and impose a traffic hazard. Thus, even the smaller bridge may be fully efficient in reducing WVC. Photos: Andreas Seiler.

These high construction costs imply that bridges and tunnels may either need to be "co-funded" through combining wildlife and human communication needs in multiple-use passages (even if this slightly reduces the feasibility of the bridge for wildlife) or the value of bridges must account for additional potential benefits of passage to wildlife and biodiversity. Well-designed bridges or tunnels can provide safe passages to a variety of animals, plants and ecosystem processes. This advantage, however, does not convey as an economic benefit and it is therefore important to bear it in mind when evaluating the economic results of bridges in a mitigation plan, especially in comparison to the much less expensive crosswalks, that, however, are only applicable to large mammals.

3.9 Roadside clearance

The role of vegetation in road verges, roadsides and adjacent forests on WVC has been discussed widely since ungulates may be attracted to palatable plants growing in roadsides or take cover in dense vegetation adjacent to roads and thus be less visible to drivers (Rea, 2003; Knapp et al., 2004; Found and Boyce, 2011; Seiler et al., 2016b). When this vegetation is kept low by frequent mowing or when visibility is increased by removing shrubs, young trees and low branches in adjacent forests, ungulates may both keep a greater distance to the roadway and be more easily detectable. However, studies that have examined the effect of vegetation clearance have found mixed results (e.g. Jaren et al., 1991; Sivertsen, 2010; Eriksson, 2014; Meisingset et al., 2014b; Rolandsen et al., 2015).

Lavsund and Sandegren (1989) observed that vegetation control in forests 20-30 m adjacent to roads resulted in a 20% decrease in moose-vehicle accidents in Sweden. Jaren et al. (1991) reported a 50% reduction in moose-train collisions on railways where vegetation was cleared up to about 30 m from the railway. Rolandsen et al. (2015) found some support for a decrease in moose-train accidents in the years following vegetation clearing, but the results were associated with a high level of uncertainty. In contrast, Eriksson (2014) found no effect of tree removal along railways in Sweden, Sivertsen (2010) reported both a decrease and an increase in WVC after roadside clearing in different parts of Norway and the study by Lindstrøm et al. (in Seiler et al., 2016b) found no effect on WVC of the removal of trees, shrubs and other vegetation at a distance of 6-25 meters from the road.

One problem associated with these inconclusive results is that vegetation clearance must be done frequently and at close intervals of 1-3 years to prevent the regrowth of palatable plants, especially Salix and birch (Child et al., 1991; Waring et al., 1991; Rea, 2003). This is of course very costly, but if vegetation recovers, it may provide even more attractive forage to ungulates than the mature plants before the treatment. Another issue is that most accidents with ungulates occur during low-light conditions when the visibility of animals outside the range of vehicle headlights is especially poor (Haikonen and Summala, 2001; Neumann et al., 2012; Rodríguez-Morales et al., 2013; Morelle et al., 2013; Steiner et al., 2014). Road reflectors, signs and other bright reflective objects in roadsides may further reduce the detectability of wildlife next to the road (Mastro et al., 2010) at night. Thus, the effect of vegetation clearance in adjacent forests may be effective only during daytime. In addition, it is also possible, that drivers may maintain a slightly higher average speed on roads where visibility is good and the terrain is open and thus compensate for the increased safety.

Thus, vegetation management in road verges and adjacent habitat does not appear as a generally promising mitigation tool against WVC. It is clearly no alternative to fencing, but may be supportive to other measures such as speed reduction or animal warning systems. Further research is needed.

3.10 Other approaches

In the attempt to find cheap but powerful solutions against WVC, many ingenious tools have been promoted to repel wildlife from roads, alert animals when vehicles approach, or teach them to behave in traffic. Ideally, these solutions would make fencing obsolete and still allow animals to cross roads when traffic is low. Such systems include active warning devices such as blinking lights and acoustic devices that are triggered by approaching vehicles and/or approaching animals (Babińska-Werka et al., 2015; Shimura et al., 2015); passive devices such as wildlife reflectors (Reeve and Anderson, 1993; D'Angelo and van der Ree, 2015), sound-generating ripples in the asphalt of roads (Ujvari et al., 2004) or ultrasonic deer whistles placed on vehicles or alongside the road (Romin and Dalton, 1992; Sullivan and Messmer, 2003; Valitzski et al., 2009); but also static solutions such as olfactory fences (Lutz, 1994; Putman, 1997; Elmeros et al., 2011). However, with a few exceptions (see www.lifestrade.it), most of these innovative approaches have not been able to produce convincing effects or have been tested sufficiently to allow for scientific evaluation (Reeve and Anderson, 1993; Ujvari et al., 1998; Gilsdorf et al., 2002; Ujvari et al., 2004; D'Angelo et al., 2006; Ramp and Croft, 2006; Huijser et al., 2008a; Huijser et al., 2009; D'Angelo and van der Ree, 2015; Van der Grift, 2016). Some of these measures lack biological relevance or signal power (reflectors, whistles, olfactory fences), while others may easily lead to habituation and thus lose their effect (lights, sounds) unless the signals are conditioned to a real threat or perceived danger (as in approaching trains). More research with well-designed experimental studies is recommended; without reliable evidence, these measures cannot be generally recommended (Van der Grift, 2016).

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Table 2. Overview of generalised estimates on the costs and effects of selected mitigation approaches. Cost-effectiveness is calculated for the measure's life length without discounting and based on the lowest costs and the highest effects on accidents. Benefit-cost ratios are calculated as net present cost ratio (NPRc, see chapter 6) for a hypothetical frequency of 2.3 WVC per km and year, with an average cost of €6,500 for accidents including moose and €4,000 for accidents without moose. The costs of increased travel times due to speed limitations are calculated for an 8,000 ADT road and a speed reduction from 90-50 km/h. Values are chosen according to the Swedish example in chapter 7. See text for more details.

Table 2. part 1 of 2

Place	Measure	installation costs in € per item or unit		life length in years	affected road length (km)	annual costs in €	Effect on WVC reduction	
		min	max				min	max
at fence end	Passive, stationary warning signs	300	500	15	0.5	10	0%	5%
	Active warning signs with speed sensor	2,000	4,000	5	0.5	50	30%	50%
	Active warning system with animal detection	30,000	50,000	15	0.5	200	30%	50%
unfenced road	Passive mobile warning sign	150	200	0.25	0.5	0	5%	20%
	Vegetation clearance in and outside road verges	3,000	5,000	4	1.0	4,000	0%	50%
	Speed reduction by 40 km/h (90-50 km/h) **	300	500	15	1.0	420,000	10%	80%
1 km fenced road	Deer-fence (primarily for larger ungulates)	40,000	40,000	15	1.0	100	25%	80%
	Fauna-fence (for both deer and smaller fauna)	45,000	45,000	15	1.0	100	50%	80%
	Fauna-fence with enforced fence base (also for wild boar)	50,000	50,000	15	1.0	150	70%	80%
only on fenced roads	Gap in fence with static speed limit and speed camera **	2,000	4,000	15	0.1	42,000	50%	80%
	Secured wildlife crosswalk with animal detection and speed reduction **	50,000	50,000	15	0.1	600	30%	90%
	Wildlife over- or underpass (20 m wide, 60 m long)	1,200,000	2,400,000	40	0.1	300	80%	100%
	Escape ramps, jump- outs	200	3,000	15	0.5	100	10%	30%
	One-way escape gates	1,500	8,000	15	0.5	100	0%	10%
	Wildlife grids (for local access roads)	3,000	5,000	15	0.1	100	50%	80%
	Gates (for rare local access)	2,000	4,000	15	0.1	100	50%	75%

Table 2. part 2 of 2

* Benefit-cost ratio 1 (without moose)		* Benefit-cost ratio 2 (including moose)		Reference	Description
best	worst	best	worst		
1.56	-1.00	3.15	-1.00	Huijser et al. 2008; Elvik et al. 2009; Putman et al. 2004; Seiler and Olsson 2015	4 standard warning signs at fence termination (on either side and in both directions), static signs on unfenced roads are not respected
1.71	-0.58	3.40	0.36	Putman et al. 2004, Swedish Transport Administration	1 unit with two illuminated signs at either ending, activated by speeding cars, costs include power supply but not travel time delays (only valid when speed limit changes with fence)
-0.45	-0.90	-0.11	-0.67	Huijser et al. 2008; Putman et al. 2004, Seiler and Olsson 2015, Henrik Wahlman, STA, pers. com.	1 unit with two illuminated signs at either ending, activated by animal detection systems, costs include power supply
-0.23	-0.93	0.25	-0.77	Huijser et al. 2008; Swedish Transport Administration, Seiler and Olsson 2015	2 mobile signs (in both directions), installed for max 1 season to locally (500m) warn drivers when outdoor activities increase wildlife mobility
-0.03	-1.00	0.57	-1.00	Lavsund and Sandegren 1991, Elvik 2009, Meisningset et al. 2014	clearing of higher vegetation, shrubs and trees in roadsides and up to 30 m from the road; must be done regularly to counteract natural succession; empirical data is inconclusive
-0.98	-1.00	-0.97	-1.00	Seiler 2005, Elvik et al. 2004, Elvik 2009	static speed reduction from 90 to 50 km/h; annual costs derive from the increase in travel time for 8,000 vehicles per average day.
1.66	-0.17	3.32	0.35	Almkvist et al. 1980, Clevenger et al. 2001, Seiler and Olsson 2015	standard exclusion fence mainly targeted at large ungulates, less suitable for smaller species including roe deer or wild boar; > 2 m in height with mesh size 10-15 cm
1.37	0.48	2.86	1.41	Iuell et al. 2003, Huijser et al. 2008; Putman et al. 2004, Seiler and Olsson 2015	same fence as above but with smaller mesh sizes at least near the base to protect small fauna
1.11	0.85	2.43	2.00	Seiler and Olsson 2015, Mats Lindkvist, STA	same fence as above, but with prolonged base that can be buried or anchored in ground to prevent being lifted by e.g., wild boar
-0.98	-0.99	-0.97	-0.98	Huijser et al. 2008; Swedish Transport Administration, Elvik et al. 2009	secured max 100 m gap in fence with permanent local speed limitation and speed camera
-0.79	-0.93	-0.66	-0.89	Huijser et al. 2008; Swedish Transport Administration, Elvik et al. 2009	secured gap in fence with animal detection and temporary (1% of year) speed reduction from 90 to 50 km/h over 100 m for 8,000 vehicles/d
-0.97	-0.99	-0.95	-0.98	Kruidering et al. 2005, Seiler et al. 2014, Seiler and Olsson 2015	bridges or tunnels with wildlife adaptations in size, substrate or design; cost €1000 - 2000 per sq. m., one per 6 km fence
11.18	0.53	18.79	1.49	Bissonette and Hammer 2000, Henrik Wahlman, STA, pers. com.	earthen ramps with ca. 2 m vertical outside wall allowing animals to exit but not enter the fenced area, one on each side per 4-6 km
1.30	-1.00	2.74	-1.00	Huijser et al. 2008, Henrik Wahlman, STA, pers. com.	one-way gates intend to allow animals to exit, but not enter; easily damaged or malfunctioning, new design in testing
1.45	0.06	2.99	0.73	Huijser et al. 2008, Allen et al. 2013, Seiler and Olsson 2015	traditional bar design is expensive and impractical in Sweden; newer mesh-design is tested, grids must be wide enough, >3 m
1.96	0.25	3.81	1.04	Seiler and Olsson 2015, Swedish Transport Administration	gates grating local access to e.g. private property; for occasional use only

4 Costs of wildlife-vehicle collisions

4.1 Accident statistics

Wildlife-vehicle collisions, especially accidents involving ungulates, have been on the rise for several decades (Mysterud, 2003; Seiler, 2004; Langbein et al., 2010; Rolandsen et al., 2011; Hothorn et al., 2012; Sáenz-de-Santa-María and Tellería, 2015). The upward trend has been explained through an increase in traffic and the recovery or expansion of deer populations (Skölving et al., 1987; Bruinderink and Hazebroek, 1996; Seiler, 2004; Apollonio et al., 2010; Sullivan, 2011; Massei et al., 2015). In Europe, Groot Bruinderink and Hazebroek (1996) estimated a minimum of 500,000 collisions a year, resulting in over 300 people killed, 30,000 injured and material damages amounting to over US$1 billion. Also in the US, the costs of WVC have been estimated to exceed US$1 billion annually (Schwabe et al., 2002).

Naturally, WVC numbers and costs vary substantially between countries. For example, in the Netherlands, Ooms (2010) estimated a minimum of 5,500 vehicle collisions occurring annually with large game species, mainly deer and wild boar. WVC are held responsible for more than 80 human injuries and an overall societal cost of €17 million. In Britain, estimates point at about 42,500 to 74,000 WVC per year, including some 425 (0.5-1.0 %) human injury accidents (Langbein et al., 2010). In Germany, according to the German Hunters Association (DJV), hunters reported about 220,000 WVC in 2007, which is about 10% of all road traffic accidents reported to the police (BMVI, 2015). Some 2,600 cases involved human injuries, i.e. 1.1% of all WVC that year.

In Sweden, official statistics on accidents with moose, deer and wild boar rose from 1,827 incidents in 1970 to 27,326 cases in 1999 (Seiler, 2004). About 60% of all police-reported road accidents referred to wildlife during the 1990s; in the northern counties up to 72%. In 2013, ungulate collisions in Sweden exceeded 50,000 and the upward trend is unbroken (Seiler et al., 2016). This includes at least 5,500 (known) accidents with moose, of which 6.7-8.3% have caused human injuries. Accidents with smaller ungulates are less severe, producing less than 100 (0.6%) cases with human injuries per year. Overall, WVC with human injuries accounted for 0.8-1.3 % of all WVC or about 2% of all road accidents with human injury during 2008 - 2014, producing an annual societal cost of more than €260 million (Seiler and Olsson, 2015; Seiler and Jägerbrand, 2016)(Table 3).

In most countries, except perhaps the Scandinavian countries, WVC appear to be generally less frequent than non-wildlife related accidents and on average not as serious for the driver. However, this picture may not be entirely accurate because not all accidents are reported to the police or detected by hunters, especially if vehicle damages are minor and no person is injured. There may also be a loss of data after a report has been issued or there may be several other sources of bias as described in Seiler and Jägerbrand (2016), leaving only part of all actual accidents contained in the final accident database. In Sweden, during 1970-1990, studies suggested that on average only about every second accident with moose and roe deer was included in the official statistics (Almkvist et al., 1980). The discrepancy was strongest for minor accidents, but even in cases with severe human injuries or deaths, there was a loss of data, probably due to accident classification issues. Since 2010, Swedish drivers are legally obliged to report any ungulate-vehicle collisions, and consequently the proportion of unreported incidents decreased to only 15% (Seiler and Jägerbrand, 2016). In other countries where animal collisions do not have to be reported, the hidden statistics are likely substantially larger (Langbein et al., 2010; Ooms, 2010). Thus, the true frequency of

WVC is inevitably underrepresented in the official statistics, and this has important implications for cost-benefit assessments of mitigation measures.

4.2 Data availability and accuracy

Another reason for the loss of data is the spatial accuracy with which WVC records are collected. When new roads are planned, expected accident frequencies can only be estimated from known relationships between, for example, game bag statistics, traffic volume, speed, road characteristics, etc. Such extrapolations necessarily introduce uncertainties that must be addressed in a cost-benefit analysis (see below). Confidence intervals for the predictions can be obtained from risk models or regression analyses (Malo et al., 2004; Seiler, 2005; Gunson et al., 2011), but where such information is missing, uncertainty levels must be assessed with precaution (maybe ± 25%). When existing roads are targeted, empirical data on WVC may exist, but even here, data accuracy may require caution. For example, up to 90% of the police reported WVC in Sweden contain geographic information provided in hunter reports after a visit to the accident site to take care of the wounded or dead animal. Even with modern GPS devices, the reported positions may, however, not always be correct or may not match with the GIS-layer of the road network. For example, about 5% of all given locations during 2010 – 2014 in Sweden could not be linked to a road (Seiler and Jägerbrand, 2016). The spatial accuracy of the useable positions was estimated to ± 250 m (Seiler et al., 2016b). Thus, the GIS data that presently can be used to calculate WVC frequencies contains less than 85% of the police-reported accidents and has a spatial resolution of 500 m. To this must be added the average loss of data during reporting (15% unreported cases) and during registration (less than 2%) as well as other potential sources for biased, faulty or lost data. Thus, Seiler and Jägerbrand (2016) recommend updating accident frequencies calculated from the official statistics by correction factors of 1.4 – 1.6 depending on road type and species.

4.3 Human injuries and other effects

Luckily, only about 1% of all WVC do involve human injuries. Cost estimates for these accidents can be obtained from national standards on traffic economy and safety (Elvik et al., 2009). Typically, these standards combine effect evaluations (based on willingness-to-pay studies) and factual costs. Typically, they distinguish between accidents with fatal, serious and minor injuries, with the value of lethal accidents being about 6-8 times higher than that of serious injuries, which in turn may be 13-20 times more expensive than light injuries, which again maybe about 10-20 times the cost of an accident without human injury (Putman et al., 2004; Elvik et al., 2009; Swedish-Transport-Administration, 2016d). These differences in socioeconomic costs and values are, however, compensated for by the relative differences in accident frequencies. Thus, the majority of costs produced by WVC is not related to human injuries, but to material damages, insurance fees and time delays. In this respect, they are mainly internal costs for the driver/car owner, implying that they actually can be addressed by adapting the drivers' behaviour and choices (Swedish-Transport-Administration, 2016b), and that they matter less from a governmental perspective. In other words, as road administrations generally focus on accidents with human injuries and may even completely disregard material damages in their economic effect calculus (as in Sweden), they will grossly underestimate the socioeconomic costs produced by WVC in total. As a consequence, road administrations may lack the political and financial incentives to promote investments in mitigation against WVC.

4.4 The value of wildlife

Road accidents with animals cannot be valued in the same way as collisions with inanimate objects such as rocks, safety rails or road signs, as is practised today. Cost estimates for WVC must also include costs related to the loss of the animal, such as the costs of the caring for dead and wounded animals, the loss of recreational and commercial values, the animal's cultural value and its value as provider of ecosystem services, its consumptive values as food or resource, its ethical and non-consumptive values, or its legal status in, for example, European directives (Mattsson, 1994; Chardonnet et al., 2002; Nilsson, 2003; Mattsson et al., 2009; ECONorthwest, 2014). Estimates of the economic value of deer in the US with regard to traffic accidents point at a range of values between 700 - 1,500 US$ (Schwabe and Schuhmann, 2002). In Sweden, estimates of the recreational and consumptive values are approximately €800 in moose, €250 in deer and €380 in wild boar (Karlsson, 2010) in (Seiler and Olsson, 2015)(Table 3). But such figures are highly dependent on the market value and are by no means inclusive of the non-consumptive ecological or ethical values, which can hardly be monetised. There have been various attempts to evaluate ecosystems (Edwards and Abivardi, 1998; Farber et al., 2002; Bateman et al., 2013), and guidelines can be obtained from the World Bank, the European Commission or organizations such as http://www.ecosystemvaluation.org, but for this report, it may suffice to recognise that the monetary values that can easily be used in CBA for mitigation measures (see Table 3) grossly underestimate the potential benefits of avoiding collisions with wild animals and of maintaining wildlife mobility across infrastructure barriers. Inevitably, CBA results are biased towards a greater reluctance to invest in mitigation. Similar to the evaluation of human life and health (Hauer, 1994; Mattsson, 2004), this drawback may be addressed through linking CBA results to a political objective, for example the desired status of wildlife populations or the level of wildlife mortality that is acceptable in traffic (Helldin et al., 2016; Van der Grift et al., 2016).

4.5 Forecasting WVC

Another critical factor in CBA is the estimation of the expected future costs and benefits. Wildlife populations are not static, nor are traffic flows or other factors that affect the frequency of WVC. Current trends in accident numbers are likely to continue, at least in the near future. Technical improvements in vehicles, such as intelligent driver assistance systems and safer car constructions, will likely further reduce the risk of human injuries in traffic, but how much remains to be seen. According to the EU Whitepaper on Transport, the number of people killed in traffic in EU countries already decreased by 40% during 2001 to 2010, and the target has been set for another 50% reduction until 2020 as result of the 'zero-vision' initiative for road safety (European_Commision, 2011). The number of other road accidents, however, and this includes 99% of WVC, is likely to increase as overall car traffic is expected to grow: freight transport by 80% and passenger transport by 51% during 2005 – 2050 (European_Commision, 2011). Also, wildlife populations are likely to continue growing.

Table 3. Average annual costs and values for wildlife-vehicle collisions in Sweden based on accident statistics from 2003 – 2012 and calculated with 2014 price levels. Source: Seiler and Olsson (2015).

Moose	Accident value in €	Average collision counts reported	Correction for underreported cases (6)	Corrected number of collisions	Estimated annual costs in €
(1) Human fatalities	3,690,000	6.2	1.26	7.8	28,782,000
(1) Severe injuries	660,000	49.3	1.53	75.4	49,764,000
(1) Light injuries	30,000	255	1.76	450	13,488,000
(2) Property only damages	4,077	4,949	1.15	5,691	23,201,420
(3) Animal values	741	5,259	1.15	6,048	4,482,267
(4) Control and hunting	111	4,733	1.00	4,733	523,501
(5) Travel time losses	11.60	5,259	1.15	6,048	70,158
Sum		5,259	1.18	6,224	120,311,345
Cost per average real moose-vehicle collision in €					19,330
Cost of average police-reported moose-vehicle collision in €					22,876

Wild boar, rein deer, roe deer, fallow deer, red deer	Accident value in €	Average collision counts reported	Correction for underreported cases (6)	Corrected number of collisions	Estimated annual costs in €
(1) Human fatalities	3,690,000	0.60	1.83	1.1	4,059,000
(1) Severe injuries	660,000	12.3	2.90	35.7	23,562,000
(1) Light injuries	30,000	73.8	3.73	275	8,259,000
(2) Property only damages	2,363	35,100	1.15	40,365	95,386,122
(3) Animal values	238	35,186	1.15	40,464	9,632,740
(4) Control and hunting	90	31,839	1.00	31,839	2,876,111
(5) Travel time losses	11.60	35,186	1.15	40,464	469,385
Sum		35,186	1.16	40,677	144,244,358
(7) Cost per average real ungulate-vehicle collision in €					3,546
(7) Cost of average police-reported ungulate-vehicle collision in €					4,099

1. Cost evaluation of road traffic accidents with human injuries and fatalities as specified in ASEK 6 standards by the Swedish Transport Administration (STA, 2016).
2. Costs of property damage only reflect average costs presented by insurance companies (Länsförsäkringar) for 2009-2012 (Jägerbrand, 2014).
3. Animal values include recreational (hunting) and consumptive (meat) values for wild ungulates (Karlsson, 2010) and reimbursement values for domestic rein deer (F. Juuso, Sámi Business & Economy, 2016).
4. Reimbursements paid to hunters or reindeer owners who are called to the accident site to take care of the dead or wounded animal (NVR, 2012). About 80-90% of accidents initiate a hunter visit.
5. Estimated loss of travel time for the driver involved in wildlife-vehicle collisions on average regardless of the damage or injury caused. Travel costs are according to ASEK 6 standards for mixed private and business travel (Swedish-Transport-Administration, 2016c)
6. Correction factors based on analysis in Seiler & Jägerbrand (2016). Costs of human injuries refer to the number of people injured as reported in the Swedish Road Accident database (STRADA) until 2012.
7. Variation in real costs among ungulate species: €3,377 in roe deer to €4,785 in wild boar; or €3,904 to €5,515 for police-reported cases.

Exchange rate from SEK to EUR: 10:1

In Sweden, for example, (Gren et al., 2015) estimated that wild boar populations could potentially increase by 80% during the next 40 years, provided that hunting pressure does not change. This is of course unlikely to be allowed and wild boar populations will be regulated through intensified hunting, but it is expected that densities may still double before regulative measures become effective. During 2003 – 2015, WVC statistics on wild boar have closely traced population development, showing a typical exponential rate of increase averaging 18.7% per year. Accidents with fallow deer and red deer increased similarly fast, by 15.5% per year, whereas collisions with moose and roe deer increased by only 2.1% – 2.4% respectively (Seiler and Olsson, 2015). If these trends continue at the same pace, then the accidents frequencies that could be mitigated in the next 20 years will be almost 50% larger than compared to what would result from the summed average frequencies that were observed in the years prior to the action. However, predicting future developments in complex systems always contains considerable uncertainties. To account for these uncertainties, sensitivity analyses or simulation models can be employed, or at least one should assign plausible alternative scenarios for the future development and present the different outcomes in relation to these. In the above Swedish case, such alternative scenarios could be a gradually diminishing rate of increase in ungulate populations or a stabilised wild boar and deer population after an initially continued increase phase of, say, 10 years. It is, however, unlikely that deer populations will stagnate entirely or even decrease in the next 20 – 30 years. The uncertainties lie rather in the rate of increase, not in the increase itself (Seiler and Olsson, 2015).

Another but nonetheless important aspect is the development in land use at the site where mitigation measure are planned. Experiences from Norway and Sweden show that even expensive investments in wildlife overpasses can be rendered ineffective when the surrounding landscape is exploited for urban or commercial development (Kastdalen, 1999) or when wildlife passages become included in the road network and are used for vehicle traffic (High Coast region in Sweden; (Seiler et al., 2003). Such developments cannot always be foreseen, but they can at least be prepared for through early multiple stakeholder participation in the mitigation plan.

5 Cost-benefit and cost-effectiveness analyses

Cost–benefit analysis (CBA) is a systematic approach to estimate the strengths and weaknesses of alternative activities for a project. The technique is used to determine which options provide the best approach in terms of benefits from time and cost savings. The transport sector applies CBA to evaluate whether an investment in measures to improve traffic flow and safety, for example, is economically worthwhile (Elvik et al., 2009; Swedish-Transport-Administration, 2016b). However, this use is not without controversy and critics such as (Hauer, 1994) have opposed the very idea of putting a monetary value on human life as this conflicts with the basic assumptions in CBA. A similar argument applies to the valuation of wildlife and nature (Spangenberg and Settele, 2010). The general problem here is twofold: CBA require a thorough estimation of both costs and benefits and assumes that both can be sufficiently expressed in monetary terms (Mattsson, 2004). While the costs of an investment may be relatively easy to assess, potential benefits are often more complex and long-term. By default, CBA tend to underestimate benefits. To account for uncertainties in estimates, sensitivity analyses, scenario techniques or Monte-Carlo simulations may be used. CBA also assume that all economically relevant benefits are subject to individual choices (Boardman et al., 2006). It is through the sovereignty of the individual consumer that the market defines the price of expenditures and gains. Both costs and benefits are often estimated through willingness-to-pay studies, for example the willingness to pay for not being injured or killed in a car accident. As such, these prices will vary over time and must thus be adjusted for the time-value of money so that all flows of benefits and costs over time are expressed on a common basis, i.e. their net present value. Most infrastructure projects have a relatively long life span (>20 years); HEATCO recommends using a 40-year appraisal period (HEATCO, 2006). Traffic safety measures, on the other hand, i.e. most measures against wildlife-vehicle collisions, have a shorter life-length (15 years)(Swedish-Transport-Administration, 2016b). Nevertheless, certain effects are expected to occur in a more distant future, and both costs and savings must be discounted in relation to the assumed changes in the market power. In other words, potential prospects on future benefits or future costs are valuated less than short-term gains. CBA outcomes are expressed as the ratio of monetary costs and benefits and result in a single number that translates to how well a project alternative may pay off. The strength of CBA is thus that they provide an absolute measure of success (see Chapter 6).

In comparison, cost-effectiveness analyses (CEA) usually compare the *relative* costs and outcomes of several actions. CEA do not answer the question whether or not a measure should be taken or an investment should be made, but they help select the measure that produces the greatest effect per invested cent. The advantage over CBA is that expected benefits do not need to be monetised but instead can be expressed in qualitative or quantitative terms and thus be directly linked to policy objectives and political targets (Tan-Torres Edejer et al., 2003). Typically, CEA are therefore expressed as a ratio of the gain in a quantifiable measure of success (e.g., number of lives saved or accidents prevented) and the economic cost associated with this gain (e.g. euros spent per accident prevented). As such, CEA can play an important role as enforcement mechanisms, helping to identify the cheapest way to accomplish a certain goal.

However, CBA can also be related to political targets and policies as they can be used to adjust the interpretation of the CB-ratio. For example, if traffic safety or environmental policy requires a certain overall reduction in WVC, then this can be used to justify mitigation even if the economic benefit may not be apparent. Examples of such policies and targets can be found in the European habitat directive with its binding regulations for governmental and private actors to maintain or restore a favourable conservation status of threatened species (Helldin et al., 2016).

Similar strategic goals exist for, for example, the reduction of human fatalities in road traffic in Sweden (Zero-vision, (Trafikverket, 2012) or the reduction of the costs of human injuries in animal-vehicle collisions (Viltolycksrådet, 2013). But where such political directives are absent or less precise, for example concerning the protection / management of common wildlife species and their ecosystem services, CBA and CEA fall short and plain economic rules may be applied. CEA and CBA are thus not supplemental but rather complementary tools that can be used in different contexts (Swedish-Transport-Administration, 2016b). In their HEATCO summary report, the European Commission gave preference to CBA, on the condition that indirect effects are included in the analysis (HEATCO, 2006).

In relation to the planning of road mitigation measures for wildlife, both CBA and CEA provide useful tools, but they also share some important constraints that will be discussed in the remainder of this report. These relate mainly to:

a. Cost-estimates on both sides of the equation must be exhaustive and accurate; this includes estimates of the costs for the investment (bridges, fences, etc.) and for its maintenance over time, as well as the cumulative costs that may be avoided or the values that may be saved by mitigation.
b. Knowledge about the efficacy of mitigation measures in reducing accident numbers or accident costs is an essential prerequisite to both CBA and CEA. This is the empirical data or reliable predictions about accident frequencies along the roads. Not all countries have sufficient knowledge of or information on both.
c. Forecasting costs and benefits over the appraisal period of a project necessarily involves uncertainties and generalizations of known trends and developments. These uncertainties may refer to the economic growth, the assumed efficacy of the mitigation measures or the anticipated change in wildlife populations.
d. Economic costs for animal-vehicle collisions must be balanced with traffic safety policy and ecological-environmental concern to develop optimal solutions. Multi-stakeholder involvement is crucial here.

6 Calculating costs and benefits

CBA compare the overall costs for mitigation measures, including future maintenance costs, with their presumed benefits in terms of saved costs due to reduced wildlife-vehicle collisions during the life-length of the project. CEA only relate the overall costs to the obtained effect on reducing WVC, such as cost per percentage of WVC reduced. In both cases, cost calculations for mitigation measure *j* are identical and can be expressed as the present net value of the costs *PVC*:

1. $$PVC_j = I_j + M_j A_n K \ ,$$

including both the investment cost *I* and the annual maintenance cost *M* for each measure, amortised by the annuity factor *A* for the economic life length *n* (product of annual discount rates) and adjusted by an additional correction factor for long-term estimations *K.* The overall mitigation cost that needs to be budgeted for in a project containing a variety of measures is simply the sum of the costs of the individual measures. Individual mitigation measures differ in their efficacy, but their efficacies may depend on or affect each other. For example, an inclusive fence system must also provide crossing facilities in the form of bridges or crosswalks. These, on the other hand, are only meaningful if combined with fences that lead animals towards the passage.

Cost-effectiveness can then be calculated as:

2. $$\mathrm{CE} = PVC_j / \sum_{t=1}^{n} e_j \ ,$$

with the effect *e* being the summed annual reduction in WVC during the project's life length *n*. Both the nominator and the denominator can also take simpler forms, for example expressing the annual CE ratio, thus without including annuities or corrections for long-term prices (compare Table 2). This is, however, not advisable when comparing economic effects over long time periods. Cost-effectiveness can be calculated per mitigation measure, but comparisons only make sense between measures that can substitute for each other. In a mitigation project that employs fencing, escape options, wildlife grids, gates, warning systems and crossing facilities, it is, however, not the efficacy of an individual measure that matters but the combined effect on WVC on the targeted road section, and thus the question of whether mitigation is economically defendable at all. Therefore the combined benefits must be estimated for all species combined during the project's lifetime. If mitigation effects and potential benefits vary a lot between species, as is the case of moose and roe deer in Sweden, calculations should differentiate between species. As with costs, benefits must be discounted for future savings and expressed as the present value benefit *PVB* for species *k*:

3. $$PVB_k = \sum_{j=1}^{l} e_{jk} \cdot L\ c_k u_k f_{kn} \cdot V_k s_k A_n K \ ,$$

with *e* being the combined effect of measures *j* to *l* to reduce collisions with species *k* on road length *L*, multiplied by the pre-mitigation accident frequency *c*, the assumed percentage of underreported cases *u* and the forecasted change in expected accidents without mitigation *f* over the project's economic life length *n*. The product is multiplied by the average economic value of a collision *V* with species *k* and the price adjustment for vehicle speed *s* (translating the species-specific increase in risk of human injuries as speed increases), adjusted by the amortization factor *A* over the project's economic life length *n* and an additional correction

factor *K* for long-term effects (Swedish-Transport-Administration, 2016b). The overall net benefit value of the project is the sum of the species-specific benefits.
Subtracting the summed costs of all measures *j* to *l* from the benefits produced for species *k* to *m* produces the net present value or factual benefit for society:

4. $$NPV = \sum_{k=1}^{m} PVB_k - \sum_{j=1}^{l} PVC_j \ .$$

Clearly, the mitigation project with the greatest NPV should be favoured – unless financial limitations require a stronger focus on cost-effectiveness. To find the cheapest solution with the greatest effect relative to the budget, one may divide NPV by the investment costs, i.e. calculate the benefit-cost ratio as:

5. $$NPRi = NPV / \sum_{j=1}^{l} I_j \ .$$

NPRi is the traditional measure to rank how beneficial a project may be relative to the initially invested capital.

If NPV is put in relation to the all costs that arise during the project's lifetime (including maintenance), one may calculate the benefit-cost ratio as:

6. $$NPRc = NPV \ / \sum_{j=1}^{l} PVC_j \ .$$

Both ratios NPRi and NPRc must be substantially greater than zero to indicate a true benefit from installing mitigation. The Swedish Transport Administration (Swedish-Transport-Administration, 2016b) recommends applying NPRi in new investment projects, i.e. new roads or new facilities such as bridges. NPRc should be preferred in projects that focus on or include maintenance and upgrading of existing infrastructure (e.g., fencing).

Given that all estimates inevitably contain uncertainties, small differences between ratios of alternative projects may not be significant or reliable. The final outcome of a CBA, i.e., the net present ratio of benefits and costs, is thus not a single value, but rather a probability function with an unknown (variable) distribution and mean. The British WebTAG[1] therefore recommends categorizing ratios into groups of benefits as given in Table 4.

Table 4. Categorised benefits of a project based on benefit/cost ratios (Swedish-Transport-Administration, 2012b).

NPRi or NPRc	value range
very high benefit	≥ 2
high benefit	1-1.99
beneficial	0.5 - 0.99
small benefit	0 - 0.49
not beneficial	< 0

To conclude, it is the ratio of the net present value over the investment or total costs that can be used as a guide in ranking and prioritising of mitigation plans. Having in mind, however,

[1] Source: https://www.gov.uk/guidance/transport-analysis-guidance-webtag

that benefits are generally underestimated, especially in respect to the value of wildlife, while investment and maintenance costs can be assessed rather precisely, the above ranges (Table 4) should be taken with caution. There may be other, non-monetary values such as traffic safety, biodiversity, or national policies that provide a counterweight to the costs and turn a small benefit into a politically desirable outcome.

7 A Swedish exercise

7.1 Benefits

Table 5 illustrates a cost-benefit exercise developed to evaluate wildlife mitigation efforts in Sweden. The hypothetical road to be treated in the example is 8.5 km in length, has on average 9,000 vehicles per annual average day at a speed limit of 100 km/h. The road did not have any mitigation against wildlife-vehicle collisions before the project started nor was it crossed by any bridge or tunnel that could be used by wildlife. Wildlife-vehicle collisions occur at the mean frequency of the top-100 WVC blackspots in Sweden (Seiler et al., in preparation). WVC-blackspots were identified with the KDE+ approach (Bíl et al., 2016) as described in Seiler et al. (2016b), have a minimum length of 6 km and a minimum WVC frequency of 6 cases during the six-year period from 2010 to 2015. A total of 14 moose collisions were reported from that road, averaging about 0.27 cases per km and year. In addition, 0.42 accidents with fallow deer were registered, 1.33 cases with roe deer and 0.33 cases with wild boar. However, due to discrepancies in data, fewer than 76% of the registered cases could be used in GIS analyses; thus the calculated collision frequencies must be increased by a factor of 1.32 to match the number of reported accidents in total.

The total number of moose-vehicle collisions that – theoretically – might occur during the economic life length of the project can be estimated by summing up the annual collision frequencies and adjusting the sum by a factor that translates the expected growth in population and traffic. Accident numbers with moose are likely continuing to increase with the expected growth in traffic, but presumably at a declining pace that represents a stabilised or somewhat diminished moose population; thus the correction factor of 0.92.

The total mitigation effect for moose, i.e. the reduction in moose-vehicle collisions achieved by the chosen combination of mitigation measures is assumed to be 90%. This presumes, of course, that all measures are optimally constructed. Efficacies in deer and wild boar are assumed to be smaller because they have shown greater abilities to overcome barriers that were effective for moose. However, if all mitigation measures are well designed and installed, the efficacies for these smaller species are likely to reach as high as levels for moose (compare also Huijser et al., 2008b).

The value of an average moose accident during the above period has been calculated at €22,334 (Seiler and Olsson, 2015). This includes costs and values related to human injuries and fatalities as listed in the Swedish Transport Economic Standards (Swedish-Transport-Administration, 2016d), the costs of vehicle repairs, costs of traffic delays, insurance fees, lost hunting values and consumptive (meat) values linked to the animal, hunter reimbursements and estimated costs for the management of WVC statistics. It further includes a correction for unreported and misclassified accidents. Not included are ecological, ethical and ecosystem values of the animal.

The average accident value must be adjusted for the speed of the involved vehicle. WVC at higher speed limits typically have a higher proportion of cases with human injuries or deaths involved and this increases the average costs; thus there is a speed-correction factor of 1.64 in moose.

The summed and adjusted values for the anticipated moose-vehicle collisions must further be adjusted for an annual standard discount rate of 4% and a standard correction factor for long-term investments (Swedish-Transport-Administration, 2016d).

In total, the present net value for all moose-vehicle collisions that can presumably be prevented during the 15 year period adds up to about €1.2 million (Table 5). The mitigation results for all species combined may produce a present value of €2.5 million.

7.2 Costs

The standard approach to reducing WVC is to install exclusion fences. A 8.5 km-long fence, however, imposes a significant movement barrier to the affected species and can disrupt seasonal migration pattern in, for example, moose (Seiler et al., 2003; Helldin et al., 2007). Also, there is a risk that animals will attempt to breach the fence in order to continue their traditional movements. Road intersections and river crossings will further provide potentially weak points in the fence where animals may enter. Thus a fenced road of this length without any further facilities to secure openings, provide crossing opportunities for wildlife or allow animals to escape once entered, will not be fully effective. It may even increase the risk of more severe accidents with wildlife since drivers will presumably pay less attention to wildlife than compared to on an unfenced road.

To be fully effective, the fence should have a reinforced base buried or anchored in the ground to prevent being lifted by wild boar. The fenced road should provide at least one safe passage, for example a crosswalk secured by an animal detection system that triggers a temporary speed reduction. In addition, jump-outs should be installed to allow animals that enter at the crosswalk or elsewhere along the fence to exit the road corridor. Intersections with local roads must be secured using wildlife grids or, if traffic is very rare, gates that can be closed. In addition, fence endings should be secured in case they cannot be connected to a suitable bridge or extended far enough into an unsuitable habitat. This can be done by active warning signs linked to an animal detection system similar to that used in the crosswalk. Alternatively, speed reductions and active speed warning signs could be used.

All these mitigation options may have an economic life length of 15 years, which is the Swedish Transport Administration's recommended standard for traffic safety measures, (Swedish-Transport-Administration, 2016b). Thus within 15 years, the investment and maintenance costs should have been outbalanced by the benefits from the accidents prevented. The costs used in this example are derived from Table 1; they add up to €604,000 in investment costs and €32,609 in discounted maintenance costs.

7.3 Cost-benefit

The resulting cost-benefit ratio or the net present value in this example is almost €1.9 million in total or an average annual benefit of about €124,329. This is indeed a very high gain and if only the necessary investment costs can be covered, this project should be prioritised in a national mitigation plan. Although this example is only hypothetical, its parameter values are realistic and representative, at least for the top-100 blackspots identified on Swedish roads (Seiler et al. in preparation). In other words, there is likely a significant socioeconomic benefit that can be gained from mitigating these blackspots. The benefit would be substantial even without the more expensive moose accidents.

However, the benefit is not large enough to balance the construction costs for a new wildlife bridge (20 m wide and 60 m long). For this, at least twice as many moose accidents would be needed per km and year. Yet, a wildlife bridge, in combination with the reinforced fences, jump-outs and secured fence endings, is likely to increase the overall efficacy of the mitigation project to 90%, also in the other ungulate species. In this case, the increase in mitigation efficacy would produce the financial benefit needed to cover the construction costs of the bridge.

In addition, since the economic life length of the bridge is longer than of fences and crosswalks, the costs can be discounted over a longer period, which most likely will increase the benefit as more accidents can be prevented in total. Thus, there is reason to prefer a bridge to a crosswalk system – if the available budget allows for the higher investment costs. Alternatively, if existing bridges could be adapted and improved to become at least partially suitable for wildlife, the potential gain from these enhancements is likely very high. Unfortunately, there is yet too little empirical evidence available to evaluate the effect of retrofitting existing bridges.

Table 5. Example of a cost-benefit calculation for wildlife-road mitigation in Sweden. For details see text. The example is available as an Excel document; see Annex 1.

1. PREMISES		
Speed limit (km/h)	100	
Economic life length (10-40 yrs)*	15	Y
Length of road to be affected (km)	8.5	L
Traffic volume (ADT)	9 000	
Expected annual growth in traffic	2%	
Discount rate	4%	
Annuity factor	11.12	A
Uncertainty factor for long-term values	1.15	K
2. MITIGATION COSTS		
Fences		
Proportion of road to be fenced	1.0	
Investment costs for the type of fence to be installed	50 000 €	I1
Maintenance costs	100 €	M1
Present value of costs for measure 1	435 870 €	PVC(1)
Escape ramps		
Number of units	4.0	
Investment costs per unit	2 000 €	I2
Annual maintenance costs per unit	100 €	M2
Present value of costs for measure 2	13 115 €	PVC2
ADS at fence endings		
Number of units	2.0	
Investment costs per unit	50 000 €	I3
Annual maintenance costs per unit	300 €	M3
Present value of costs for measure 3	107 673 €	PVC3
Crossing structures		
Number of bridges/tunnels suitable for wildlife	-	
Investment costs per structure	2 000 000 €	I4
Annual maintenance costs per structure	300 €	M4
Present value of costs for measure 4	- €	PVC4
Crosswalks		
Number of units	1.0	
Investment costs per unit	50 000 €	I5
Annual maintenance costs per unit	300 €	M5
Present value of costs for measure 5	53 836 €	PVC5
Passive warning signs		
Number of units	4.0	
Investment costs per unit	250 €	I6
Annual maintenance costs per unit	- €	M6
Present value of costs for measure 6	1 000 €	PVC6
Wildlife grids, gates, etc		
Number of units	4.0	
Investment costs per unit	5 000 €	I7
Annual maintenance costs per unit	100 €	M7
Present value of costs for measure 7	25 115 €	PVC7

Other mitigation …		
Number of units / Proportion of road affected	-	
Investment costs per unit / per km	- €	I8
Annual maintenance costs per unit / km	- €	M8
Present value of costs for measure 8	- €	PVC8

Present value of summed costs (PVC)	636 609 €	PVC
Present value of investment costs (PVCi)	604 000 €	PVCi
Present value of maintenance costs (PVCm)	32 609 €	PVCm

3. BENEFITS		
MOOSE		
Value of average accident	22 334 €	V(m)
Correction for cost per speed class	1.64	S(m)
Accident frequency per km and year	0.270	C(m)
Correction for missing data	1.32	U(m)
Expected total mitigation effect	0.900	E(m)
Correction for prediction effects	0.92	F(m)
Present value benefit	1 176 066 €	PVB(m)
Fallow/Red deer		
Value of average accident	5 052 €	V(d)
Correction for cost per speed class	1.16	S(d)
Accident frequency per km and year	0.420	C(d)
Correction for missing data	1.32	U(d)
Expected total mitigation effect	0.700	E(d)
Correction for prediction effects	1.56	F(d)
Present value benefit	384 156 €	PVB(d)
Roe deer		
Value of average accident	3 971 €	V(r)
Correction for cost per speed class	1.46	S(r)
Accident frequency per km and year	1.330	C(r)
Correction for missing data	1.32	U(r)
Expected total mitigation effect	0.700	E(r)
Correction for prediction effects	0.95	F(r)
Present value benefit	733 365 €	PVB(r)
Wild boar		
Value of average accident	5 127 €	V(b)
Correction for cost per speed class	1.13	S(b)
Accident frequency per km and year	0.330	C(b)
Correction for missing data	1.32	U(b)
Expected total mitigation effect	0.500	E(b)
Correction for prediction effects	1.52	F(b)
Present value benefit	207 954 €	PVB(b)
Other species		
Value of average accident	- €	V(o)
Correction for cost per speed class	1.00	S(o)
Accident frequency per km and year	-	o(o)
Correction for missing data	1.00	U(o)
Expected total mitigation effect	-	E(o)
Correction for prediction effects	1.00	F(o)
Present value benefit	- €	PVB(o)

Other species		
Value of average accident	- €	V(o)
Correction for cost per speed class	1.00	S(o)
Accident frequency per km and year	-	o(o)
Correction for missing data	1.00	U(o)
Expected total mitigation effect	-	E(o)
Correction for prediction effects	1.00	F(o)
Present value benefit	- €	PVB(o)
Present value of summed benefits (PVB)	2 501 541 €	Sum (PVB)

4. COST-BENEFIT		
Net present value (NPV)	1 864 932 €	PVB-PVC
Net present value ratio (NPR)	3.09	NPV/PVC
Overall benefit-cost ratio (PVB/PVC)	0.25	PVB/PVC
Benefit evaluation:	very high benefit	

n = Economic life length of the entire mitigation project, assuming all measures have the same life length
L = Length of the road where mitigation effort will be effective
A = Annuity factor for given discount rate and life length (from tabulated data in Swedish-Transport-Administration, 2016a)
K = Additional correction factors for long-term costs (if applicable)
I = Investment cost
M = Average maintenance cost per year
V = Socioeconomic value of average accident
s = Correction for accident costs in relation to speed; higher speed involves a higher risk of severe human injury
c = Collision frequency (WVC per km and year); as measured or expected from empirical data
u = Correction for missing data or underreported accidents (available empirical data is incomplete and biased)
e = Expected reduction in WVC achieved by the combined mitigation measures
f = Correction for the forecasted change in accident numbers compared to baseline
PVC(i) = Present value of investment cost
PVC(m) = Present value of discounted maintenance costs = Sum of (M*A*K)
PVC = Present value costs (sum of investment and discounted maintenance costs)
PVB = Present value benefit (saved discounted costs and values) = Sum of (V*S*C*U*E*f*L*A*K)
NPV = Net present value

8 Strategy for mitigation

As described earlier, there are many shortcomings and problems associated with the monetary evaluation of benefits and costs of mitigation against wildlife-vehicle collisions. Cost-benefit analyses must hence be interpreted with caution. In the practical application, however, decision-making may not be so difficult after all, simply because the available options are so limited. Road planners have but a few measures to choose from, given the present state of knowledge. And these can be further narrowed down if put into a road and traffic context.

In principle, one may distinguish between the following categories:
1. motorways and major transportation corridors with high traffic volumes, high speeds and multiple lanes;
2. intermediate roads with identified WVC hotspots;
3. intermediate roads where WVC are frequent but not aggregated;
4. intermediate and minor roads with only occasional WVC and no apparent spatial pattern.

8.1 Category 1: motorways

For the major transportation corridors consisting of multi-lane motorways with high traffic volumes, high operative speed, often with central barriers, verge railings or even road lighting, there is no other solution than to separate wildlife and traffic permanently. This can only be achieved by inclusive fencing systems that combine escape opportunities, driver warnings at fence openings, extended fences along connecting roads and crossing structures. Even if present WVC numbers are low, which could be an effect of the repelling traffic (Seiler et al., 2016a), fencing and bridging may be mandatory because the risk of human injury, secondary accidents and consequent traffic problems is very high in each single accident.

Ideally, to provide safe and efficient long-distance transportation, such major routes should be completely shielded or isolated from the surrounding landscape with its wildlife, people and local infrastructures. They are thus significant ecological barriers to most terrestrial wildlife, not to ungulates alone. But by the same token, they will be perforated by many conventional bridges and tunnels built for local communication. These crossing structures often provide more or less suitable passages for wildlife that could be improved or retrofitted to enhance their use and reduce the “pressure” on the fences between them. Where the distance between structures is very large, however, there may be a need to build new bridges that again could serve multiple purposes at lower construction costs.

How these major transportation corridors are distinguished with respect to traffic, speed or safety objectives is a political question and not subject to a cost-benefit analysis. The definition of the maximum distance between the nearest crossing structures suitable to wildlife may be rooted in empirical evidence, ecological theory or defragmentation strategies (Hlavac and Andel, 2002; Trocmé, 2005; Bissonette and Adair, 2008; Bekker et al., 2011; Seiler et al., 2015a). Once these criteria are defined, a CBA may help to rank mitigation tasks in relation to existing WVC problems and identify those road sections where the net benefits are largest.

8.2 Category 2: intermediate roads with WVC hotspots

Where WVC aggregate at high frequencies and repeatedly over periods of time, mitigation may be required from road administrations, irrespective of the type of road, its traffic volume or operational speed. The advantage is that such WVC hotspots are typically rather short and can thus easily be targeted in mitigation plans. A CBA may be helpful in two ways: a) for defining hotspots by setting a global economic threshold for the minimum number of accidents required; and b) for prioritising the mitigation needs. The final components in the mitigation package are not much different from the options applicable to category 1: an inclusive fencing system with crossing facilities where needed. In contrast to motorways, however, it may here be possible to impose temporary and sudden speed reductions without the risk of rear-end collisions and consequent human injuries. If speeds can be reduced – either enforced through speed limits or voluntarily by the individual driver - it may be possible to separate wildlife and traffic on time, allowing animals to cross the road at grade level. This can be achieved by crosswalks and secured fence endings. These solutions are substantially cheaper than bridges or tunnels and they could be moved and reinstalled if WVC hotspots develop elsewhere (Huijser et al., 2015b). A CBA may also help to identify locations where even bridges may be economically defendable, especially if wildlife species other than large mammals may benefit from a safe and permanent passage and their values can be included in the analysis.

Hotspots in WVC have been identified in various studies and with different techniques (Ramp et al., 2005; Montella, 2010; Shilling and Waetjen, 2015; Bíl et al., 2016). Our own research on Swedish and Spanish WVC revealed that significant WVC clusters (with more than 1 accident per year and km on average) occupied but a small fraction (about 1%) of the public road network but contained about 20% to 45% of the recorded accidents (Seiler et al., 2015b; Torellas, 2015; Seiler et al., 2016b). Ongoing studies suggest that, by definition, most of these clusters produce a significant cost-benefit ratio and thus qualify for mitigation investments (Seiler, in preparation). Thus, by mitigating hotspots, i.e., category 2 roads, it may be possible to reduce WVC at the national level by perhaps up to 40% or maybe even more, depending on the species concerned and on how aggregated WVC occur in the road network. Clearly, it is here where road administrations should focus their mitigation efforts, but caution is advised (Elvik et al., 2009) as further research is still needed to fully understand the spatio-temporal factors that cause hotspots.

8.3 Category 3: intermediate roads with frequent but dispersed WVC

While categories 1 and 2 are relatively simple cases from a planning perspective, category 3 roads are more difficult to address as there is neither a clear political incentive (as in cat. 1) nor a likely economic benefit (as in cat. 2). Road sections with very high WVC frequencies that are not recognised as hotspots can still qualify for mitigation similar to cat. 2 roads. The difference may be simply a matter of scale applied in the definition of hotspots. The problem, however, is that these roads will be generally longer than hotspots and thus require longer fences, more exits, gates, etc. and more crossing facilities. A CBA in concert with a thorough analysis of WVC patterns will help to identify where such mitigation may still be economically defendable.

For the remaining road sections, where fencing is not an option, alternative methods to reduce WVC need be developed. By definition, these roads comprise a much larger part of the public road network than do cat. 1 and 2 roads and also produce the major part of all

WVC at the national level. Hence, they cannot be ignored in a mitigation strategy, but may not be an appropriate target for road administrations alone. Instead, multiple stakeholders, the general public, automobile industries and transport users will have to cooperate in sharing costs and incrementally improving conditions in traffic, road and landscape that make WVC less likely to occur. Solutions will most likely be found in combinations of measures, such as roadside clearance together with night-vision driver assistance systems or adaptations in forestry practices together with temporary speed reductions or mobile warning signs, in-car warnings based on risk prediction models and the vehicles' GPS in concert with public education and participation programmes in issuing wildlife warnings to following drivers. Even scaring devices that alert animals rather than drivers may probably prove to be effective. More research and experimental studies are needed and should be encouraged by society at large. Yet, it should be clear that the focus of such methods should be on reducing the risk of relatively rare and unpredictable events. Cost-effectiveness analyses may here be useful to identify the most promising approaches.

8.4 Category 4: intermediate and minor roads with occasional WVC

WVC on minor roads with low traffic and low speed will be practically impossible to address for road administrations, mainly because WVC are rather infrequent and dispersed and thus difficult to target, but also because WVC with human injuries on such roads are rare and thus the average costs are low. Instead, mitigation against WVC may only derive from global changes in, for example, the knowledge and behaviour of drivers or in vehicle safety technology. Hence, neither a CEA nor a CBA may be feasible at present. After all, it must be recognised that wildlife-vehicle collisions can never be completely eliminated as long as vehicles and animals utilise the same infrastructure.

9 Checklist for using a CBA/CEA

The following list of tasks may be helpful in conducting cost-benefit analyses for mitigation plans against wildlife-vehicle collisions.

1. **Delineate the extent and scope of the mitigation project**
   Set the geographic extent of the project and its expected mitigation effect, specify traffic and infrastructure characteristics, define the target species and identify relevant stakeholders that may be affecting or affected by the mitigation project in the future.

2. **Specify mitigation objectives, set targets**
   Define the desired outcome in relation to existing mitigation policies, safety guidelines, defragmentation strategies or other relevant land use development plans. Refer to or develop objectives for improving traffic safety and reducing wildlife mortality and road barrier effects. Cooperate with relevant stakeholders and other involved interests in this work.

3. **Identify what type of mitigation may be required**
   Based on the local conditions, identify how the mitigation package should be composed: approximately how much fencing, how many exit ramps, how many fence endings and warning system, how many crossing structures and crosswalks may be needed to effectively secure the road and provide sufficient opportunities to cross. These settings can be tweaked later.

4. **Obtain estimates for investment and maintenance costs of potential mitigation measures**
   Standard values for construction or material costs, for example, may deviate from current market prices; costs may be reduced if standard techniques and methodology are available; measures can be mass-produced or competition is high among potential consultant companies. Include monitoring or follow-up studies in maintenance costs.

5. **Define the economic life length of the measure/project with reference to the time scale where mitigation effects can be assumed**
   Economic life lengths for road measures are often standardised. Wildlife mitigation projects can, however, involve measures with very different life lengths. This must be considered in the analyses.

6. **Estimate the expected accident frequencies without mitigation over the entire life length of the measure/project and provide estimates of uncertainties, develop scenarios**
   Wildlife populations as well as traffic flows are not static but change (increase) over time. Their increase will entail an increase in WVC. Hence, mitigation works can be expected to prevent more accidents in the future than compared to the observed mean during the past 5-10 years. This can be of significance to cost-benefit analyses as it will increase the potential benefit. Uncertainties in forecasted WVC and thus costs can be evaluated using scenarios or Monte-Carlo simulations.

7. **Estimate the expected efficacy of mitigation measures and provide confidence intervals or ranges for the estimates**
   Based on available evidence, efficacies in accident reduction can vary substantially between species, measures and different designs. Utilise this variation to define levels of uncertainty in estimates.

8. **Estimate the overall costs of WVC for the society at large as extensively as possible (e.g., material damage, societal costs, value of wildlife) and specify which costs/values are not included**
   The economic value of a WVC largely depends on the value of the animal, repair costs of the vehicle and management costs related to the accident. Costs of human injuries are substantially higher, but occur in only about 1% of the WVC. Furthermore, these costs are only one part of the overall sociological, cultural, ethical and ecological value of wildlife. As long as these values are not monetised and included as political objectives, CBA will inevitably be biased towards a greater reluctance to invest in mitigation.

9. **Make a case for wildlife-vehicle collisions**
   Traffic safety policy in Europe strongly focuses on reducing human injuries and fatalities in road traffic. This focus necessarily leads to ignorance towards accidents with mere damage to personal property. Most WVC, however, fall into this category and are thus not considered in effect calculations of road administrations. In addition, accidents with animals are not the same as accidents with inanimate objects because of the intrinsic and societal values of wildlife. Road administrations must realise this and develop appropriate evaluation tools or define policies and objectives to reduce WVC that CBA can relate to.

10. **Apply evaluation results with caution**
   CBA and CEA produce a single figure that summarises the overall result and that can be used to compare alternative mitigation solutions or plans. However, because benefits related to wildlife are necessarily underestimated while investment and maintenance costs are calculated rather precisely, the cost-benefit ratio must be taken with caution. There may be other, non-monetary values or specific policies that provide a counterweight to the costs. They do not show up in the calculation results, but must be applied afterwards to adjust outcome thresholds in the final interpretation. In fact, they may well turn a small economic benefit into a politically desirable outcome.

10 Conclusions

CBA is a useful tool in planning mitigation actions against wildlife-vehicle collisions. However, it must be used with caution since it is inevitably biased towards a greater reluctance to invest in mitigation. Policy or political targets should therefore be involved in the interpretation of CBA results. CEA allows the comparing and ranking of alternative mitigation strategies or measures. But as a successful mitigation plan includes several types of measures that influence each other in their effect on WVC, the question is rather not whether one measure performs better than another, but whether mitigation is economically defendable or politically advisable to begin with.

Luckily, only a few WVC involve human injury or death. However, due to the strong political focus in Europe on reducing human fatalities on roads, it is only those few WVC that become visible in the economic calculus of the transport sector. The vast majority of WVC that only lead to property damage – and, of course, to the loss of wildlife – are largely ignored. In addition, WVC are typically regarded in the same way as other property-damage only accidents with inanimate objects such as rocks, rails or traffic signs. By ignoring the ecological, ethical and societal value of wildlife, the potential benefits of preventing WVC are strongly underestimated. Studies demonstrate, however, that when all WVC and all available cost estimates are considered, there is a significant socioeconomic benefit that can be gained from investing in mitigation. To achieve this benefit and reduce WVC effectively, a new attitude towards WVC may be needed together with a clearly outlined policy and quantifiable mitigation targets.

In addition, we have so far focused on mitigation designed to reduce accidents with large mammals, especially ungulates. Many of these measures, but not all, will also be advantageous to other wildlife that may be disturbed more severely or even threatened in their survival by road traffic. These ecological benefits are not monetised and thus do not contribute to the economic result of a CBA. Hence, they must be involved through policy and via the framework that defines the rules for interpreting a CBA.

At present, only a few measures with proven effect on WVC are available to road administrations and these consist mainly of a traditional and static inclusive fencing system combined with crossing facilities such as crosswalks or bridges. These measures must and can be applied either to major transportation corridors (where there is political incentive to permanently isolate traffic from animals) or to road sections with especially high frequencies of WVC (where an economic benefit is likely). These road sections may contain a substantial proportion of all WVC, but represent only a small fraction of the road network. Thus, with relatively small but well-targeted mitigation efforts, WVC can likely be significantly reduced at the national level. That this has not already been achieved is probably due to the focus on accidents with human injuries. Mitigation measures against WVC may not have been located where they can produce the greatest reduction in accident numbers, but where the risk of human injuries was highest.

Nevertheless, a very large share of WVC is still too erratic and too dispersed over the road network to be effectively addressed by the local measures available to road administrations. Other stakeholders and actors must be involved and develop mitigation approaches that address global or landscape-scale factors. Promising options are, for example, the animal detection and driver assistance technology of automobile companies, but also public participation programmes that help increase awareness among drivers. Other approaches, such as hazard prediction models and driver warning apps, may help to further concentrate driver attention during those times and on those roads where accident risks are highest.

And yet again, adjusting the traffic safety policy and environmental objectives of the transport sector may provide the necessary support to encourage other actors in society to cooperate against WVC. Clearly, there is no single magic measure that can solve WVC on all roads; instead we must combine different measure on different scales and from different actors to produce the desired improvement. This also calls for continued research and experimental studies to refine existing measures and develop new, more cost-effective alternatives. But given the socioeconomic benefits that can already be gained from mitigating traffic problems with ungulates alone and the possibilities of sharing costs and obligations among sectors and among countries as well, there should be incentive enough to take action.

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Annex 1

Excel document with Cost-benefit calculation presented in Table 5. Available on project website: http://www.saferoad-cedr.org/en/saferoad/documents.htm

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