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Optimal road design through ecologically sensitive areas considering animal migration dynamics

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ABSTRACT

With increasing land transportation requirements in both urban and rural areas, roads are encroaching ever more on animal habitats, where collisions with vehicles are a leading contributor to wildlife mortality. While road designers recognise the importance of accounting for such impacts at the design level, existing approaches simply either ignore viable habitat or avoid such regions entirely. Respectively, this can result in road alignments that are overly damaging to vulnerable species or prohibitively expensive to build and operate. The research presented in this paper investigates the effects of explicitly accounting for animal mortality on the design of a road through an ecologically sensitive area. The model presented achieves this by incorporating a spatially-explicit animal migration and road mortality model into an accepted optimal road alignment algorithm to propose low-cost roads that maintain the animal population above a minimum threshold by the end of a specified design horizon. The new method was applied to an example scenario to demonstrate the effect of setting a minimum required animal population on the road design. This model was able to consistently produce a road that met a minimum required species conservation benefit. This reflected a major improvement over the model that ignored animal habitats while only requiring a minor increase in construction and operating costs compared to the model that avoids habitat.

1. Introduction

Roads are an integral part of modern transportation networks and much work has been done to develop algorithms that produce low-cost road alignments through real terrain that incorporate many realistic cost features and constraints (Kang et al., 2012). However, roads also affect surrounding wildlife populations (Forman and Alexander, 1998; Friedrich, 2015) and in some cases, these impacts are the deciding factors in selecting the final road design (Kang et al., 2009). Therefore, it is crucial to properly account for these ecological effects during the road alignment optimisation process.

Similarly, while ecological models can account for many of the negative impacts of roads, they currently only focus on existing roads or general policy recommendations. As animal populations can be highly sensitive to the actual route taken by a road, it is imperative that these ecological models be incorporated during the calculation of a new road's path. This will

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allow road designers to determine optimal alignments while also maintaining the long term ecological sustainability of new roads.

Optimal road design through a three dimensional terrain consists of two principal components: horizontal alignment, which is the road path when viewed from above; and vertical alignment, which is the road profile. The overall objective is to minimise the expected present value of road construction costs and lifetime operating costs subject to numerous constraints. Many different approaches have been considered in the literature for road design to date: variational calculus, network optimisation, dynamic programming, enumeration, linear programming, numerical search, distance transformation, neighbourhood search heuristics, genetic algorithms (Kang et al., 2012) and derivative-free approaches (Mondal et al., 2015). Of these, seven have successfully been applied to simultaneously solving horizontal and vertical alignments: numerical search using variational calculus (Chew et al., 1989), distance transforms (De Smith, 2006; Li et al., 2016), neighbourhood search heuristics (Aruga, 2005; Shafahi and Bagherian, 2013), genetic algorithms (GA) (Jha et al., 2006; Jong and Schonfeld, 2003; Kang et al., 2012; Kim et al., 2005; Maji and Jha, 2012; Mishra et al., 2014), dynamic programming (Li et al., 2013) and derivative-free methods (Mondal et al., 2015). Of these approaches, evolutionary-based techniques such as genetic algorithms have been the most widely-investigated due to their ability to realistically handle the complex fitness functions featuring non-linearities and discontinuities while including mechanisms to escape local optima.

Despite their success, some important limitations of GAs must be mentioned. The first is that they do not guarantee optimality (including local optimality). They simply allow finding less-expensive road profiles. Furthermore, the stochastic nature of the algorithm means that the same solution may not be achieved each time the algorithm is run. Additionally, a very large number of evaluations are required to sufficiently explore the solution space, which can cause tractability problems, particularly if the evaluation function is computationally expensive (Jin, 2011). There are black-box optimisation tools such as NOMAD (Abramson et al., 2016; Audet et al., 2009) and Hopspack (Plantenga, 2009) that implement derivative-free approaches (Audet and Dennis, 2006) to overcome some of these issues. Such tools are fast and guarantee at least local optimality. This has been successfully applied in the work of Mondal et al. (2015) in which the authors develop a very efficient and robust bi-level optimal road design model in a specified corridor where optimal earthwork costs are computed using Mixed Integer Linear Programming (Hare et al., 2014). Finally, in another recent paper, Li et al. (2016) extend the distance transform approach of De Smith (2006) to consider highly-constrained railway alignments in mountainous regions using adaptive neighbouring masks and a bi-directional scanning strategy. This method addresses the difficulty of finding suitable alignments through complex mountainous terrain.

In addition, recent literature into optimal road design also recognises the increasing importance of adequately accounting for socio-economic and environmental effects of these designs (Kang et al., 2012; Mishra et al., 2014). For instance, in industries such as mining, where new roads are regularly built, regulators and communities at large could potentially shut down operations if they breach social and environmental constraints (Cruz and Wakolbinger, 2008; Prno and Slocombe, 2012). On public roads, the damaging effects on wildlife are also becoming increasingly dominant. For example, in the United States, it is estimated that anywhere between 15 and 20% of land mass is already ecologically impacted by roads (Forman and Alexander, 1998) with vulnerable species being affected through mechanisms such as habitat fragmentation and degradation, modification of animal behaviour and vehicle collisions (Dique et al., 2003b; Jaeger et al., 2005).

While road design algorithms can be modified to apply penalties to roads traversing animal habitats (Kang et al., 2012; Jong and Schonfeld, 2003; Chew et al., 1989; Kim et al., 2005; Maji and Jha, 2012), current approaches are too simplistic. In these cases, an arbitrary penalty cost is applied to sensitive regions of the map. This approach unfortunately ignores the dynamics of animal behaviour, which depends on the overall road path and its effects on highly mobile species. This has the potential to produce designs that mask these important dynamics, thereby creating roads that may either be too expensive to construct and operate or too damaging to nearby animal populations.

Fortunately, empirical studies have measured ecological impacts of roads. For example, Fahrig and Rytwinski (2009) conducted a large survey on quantifiable measures of the impacts of existing roads on a number of animal species due to various mechanisms. These include noise, pollution and habitat fragmentation. In another study, Jaarsma (1997) investigated the effects of "traffic-calmed rural areas" in reducing contact with animal species. They found that the ability to route traffic along high capacity distributor roads to accommodate increasing traffic volumes results in greater species survival in the long run.

Empirical studies based on real-world data such as these have formed the basis for models to evaluate proposed road designs. For instance, van Langevelde and Jaarsma (2009) extended the work of Jaarsma (1997) to investigate the effects of different traffic policies within an existing network on species survival when traffic volume is varied. Focusing instead on fixed traffic volumes, Frair et al. (2008) assessed different road alternatives in the vicinity of habitat zones by varying road density. In another study, Rhodes et al. (2014) used a comprehensive animal movement and mortality model from Rhodes et al. (2005) to show scenarios under which it is suitable to build many smaller roads or fewer large ones. This model used specific species data relating to relative habitat preference, foraging and home ranging behaviour and the location of vegetation throughout the region to develop realistic transition probabilities for animals in the region. These transitions have corresponding survival probabilities that are related to the traffic volume and the number of road crossings required.

The model of Rhodes et al. (2014) was also used in Davey et al. (in press) to observe the effect of optimally controlling traffic flow over time to maintain a species population above a critical threshold while maximising the present value of the road. This was used to select the most valuable road to build among a fixed set of candidate roads.