CHAPTER 16

TRAFFIC MORTALITY, ANALYSIS AND MITIGATION

Effects of road, traffic, vehicle and species characteristics

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Abstract. This chapter focuses on the impact of transportation on wildlife. Measures are frequently applied to mitigate these impacts. Most measures involve technical devices that change the road characteristics. However, also other measures may reduce traffic mortality, such as reduction of traffic volume or speed, and periodic closing of roads. For effectively applying these mitigating measures, insight in the effects of road and traffic characteristics on traffic mortality is needed. We argue that the success of measures that mitigate habitat fragmentation by roads drastically increases when minor roads are integrated in transportation planning. We discuss a strategy based on the concept "traffic-calmed rural areas", where the effects of minor and major roads are not mitigated separately, but in coherence. To enable transportation planning to include the impacts on wildlife in the planning process, we present a traversability model derived from traffic flow theory that can be used to determine the probability of successful road crossings of animals based on the relevant road, traffic, vehicle and species characteristics. We apply this model in a case study in The Netherlands to evaluate different scenarios. Several levels of traffic calming are compared with the autonomous development, which shows that traffic calming can drastically reduce traffic mortality.

1. INTRODUCTION

"Transport's impact on the environment is multifaceted and can be severe" (Button and Nijkamp, 1999; p xiii). A wide range of impacts has been studied, such as traffic safety (Elvik and Vaa, 2004), noise (Lee et al., 1998), emissions (Sharma and Khare, 2001), and vehicular-related air quality (Sharma et al., 2004). In this chapter, we focus on the impact of transportation on wildlife. Infrastructure is one of

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the principal causes for the fragmentation of their habitat (Andrews, 1990; Forman and Alexander, 1998; Spellerberg, 1998; Trombulak and Frissell, 2000). There are at least four negative effects of traffic on wildlife (Van Langevelde and Jaarsma, 2004): destruction or alteration of habitat due to construction, disturbance of habitat along the road or railway (noise, vibrations, car visibility, etc.), barriers created by the road or railway (increased resistance for movements), and barriers by traffic (collision risk during crossing). The first two directly affect the habitat of the species. They result in a decline of habitat area or strips along the road with lower quality of habitat. The latter two effects have an impact on individuals. These four effects may have implications for population dynamics and community structure near the road. We mainly focus on the mortality due to traffic on roads. Here, we define the traversability of a road as the probability of successfully crossing that road by an individual.

Measures are frequently applied to reduce traffic accidents (Garret and Conway, 1999; Singh and Satheesan, 2000) and protect biodiversity (Van Bohemen, 1998; Trombulak and Frissell, 2000). Mitigation measures include keeping wildlife off the road (e.g., fences: Romin and Bissonnette, 1996; Putman, 1997), providing alternative routes (e.g., fauna passages and ecoducts: Jackson and Griffin, 1998; Keller and Pfister, 1997) or reducing the risk of collisions (e.g., highway lighting or mirrors: Romin and Bissonette, 1996; Putman, 1997). Most measures involve technical devices that change the road characteristics. However, also other measures may reduce traffic mortality, such as reduction of traffic volume or speed, and periodic closing of roads (during the night or a specific season). For effectively applying mitigating measures that reduce traffic mortality at locations where no passageways or fences are constructed, insight in the effects of road and traffic characteristics on traffic mortality is needed (Andrews, 1990; Kirby, 1997; Forman and Alexander, 1998). We argue that the success of measures that mitigate habitat fragmentation by roads drastically increases when the minor roads are integrated in the planning of the measures (Jaarsma and Willems, 2002a; Van Langevelde et al., in prep). In this chapter, we discuss a strategy based on the concept of a traffic-calmed rural area (Jaarsma, 1997), where the effects of the minor and the major roads are not mitigated separately, but in coherence.

For a sound planning and design of measures to mitigate environmental impacts of transportation, quantitative models are available that calculate impacts such as noise and pollution. These models enable to predict the impacts of (alternative) plans for infrastructure in quantitative terms such as numbers of hindered people. This is in contrast with impacts of these plans on plants and animals, where at most the acreage of destroyed habitat by the road construction can be quantified. However, the impacts on wildlife movement, essential for both daily and seasonal activities of individuals of a species and generally affecting its population dynamics, remain unknown. To compare alternative solutions for the road network with respect to wildlife movement, a more quantitative approach is desirable. We developed a model for successful wildlife crossings of a road (Van Langevelde and Jaarsma, 2004; Jaarsma et al., in prep). In this chapter, we present this model and review relevant road, traffic, vehicle and species characteristics to estimate the probability of successful road crossing (based on Van Langevelde and Jaarsma, 2004 and revised in Jaarsma et al., in prep.). In contrast to other recent studies on traffic mortality (Van Langevelde and Jaarsma, 1997; Jaarsma and Van Langevelde, 1997; Hels and Buchwald, 2001; Clevenger et al., 2003; Jaeger and Fahrig, 2004), we explicitly derived the model from traffic flow theory.

The aim of this chapter is to combine knowledge on movements of animals with knowledge on headway distributions on roads in a traversability model and to illustrate its value in a case study. Therefore, we first shortly review literature on environmental impacts of roads and traffic on wildlife. A model to estimate traffic mortality is discussed based on theory of traffic flows. This model can estimate the change of the number of traffic victims among traversing animals before and after mitigating measures, and/or for alternative infrastructure network solutions relative to the present situation. We then apply the model in a case study in The Netherlands to evaluate different scenarios. In this chapter, we summarize our earlier work.

2. ROADS AND TRAFFIC: IMPACTS ON WILDLIFE

Seiler (2002) and Forman et al. (2003) review a wide range of direct and indirect effects of infrastructure on nature. Indirect effects follow the construction of new roads or railways, for example, consequent industrial development or changes in human settlement and land use patterns. We focus on effects that directly impact wildlife and their habitat, as these are usually the most relevant to the transport sector. Direct ecological effects are caused by the physical presence of the infrastructure section and its traffic flows. Generally accepted is the next categorization into five major categories: habitat loss, corridor habitats, disturbance and edge effects, barrier effects, and mortality (Van Langevelde and Jaarsma, 2004). Figure 1 presents a schematic representation. Together, these effects result in habitat fragmentation, *i.e.*, the subdivision of natural habitats into small and isolated patches. It leads to conditions whereby species, as well as their populations, are endangered and extinctions might occur. Habitat fragmentation has been recognised as a significant cause for the decline of biodiversity (Seiler, 2002; Forman et al., 2003), and are thus a major concern for society.

2.1 Habitat loss

Habitat loss is an inevitable consequence of infrastructure construction. A part of the surface of a new road is paved and therefore it is consequently lost as natural habitat for plants and animals. Motorways may consume more than 10 hectares of land per kilometre of road. Rural highways and minor rural road occupy (much) less area per kilometre, but collectively they comprise at least 95% of the total road stock. Hence, their cumulative effect in the landscape can be considerably greater (Jaarsma and Willems, 2002a; Seiler, 2002). One should realise that associated features, such as verges, slope cuttings, parking places, and service stations etc., also claim space. So, the total area designed to transport is several times larger than the paved surface. It is estimated to be 5-7% of the land surface in rather densely populated Western-European countries such as The Netherlands, Belgium or Germany (Jedicke, 1994).

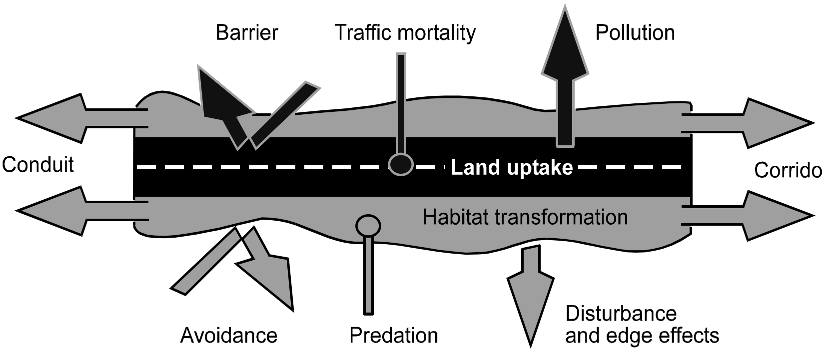

Figure 1. Schematic representation of the five direct ecological effects of infrastructure: habitat loss (land uptake, habitat transformation), corridor habitats (corridor, conduit), disturbance and edge effects (avoidance, pollution, predation), barrier effects (by unsuitable habitat/disturbances, repelled by traffic or road characteristics, physical hindrances), and traffic mortality. Together these impacts lead to the fragmentation of habitat (source: Seiler, 2002; p 32).

For Sweden, where transportation infrastructure is sparser, roads and railways are estimated to cover about 1.5% of land surface (Seiler and Erikson, 1997). The USA devotes about 0.45% of its land area to roads, based on the average road density of about 0.75 km/km^2 (Forman et al., 2003). These authors estimate that adding the right-of-way of these roads would roughly double the amount of land devoted to roads. They state that even this crude estimate is a significant underestimation because it excludes private roads in sub-urban areas as well as driveways and parking areas.

2.2 Corridor habitats

Road verges considerably vary between different landscapes and countries. Despite verges are highly disturbed environments, numerous inventories indicate the great potential of verges to support a diverse range of plant and animal species (Munguira and Thomas, 1992; Seiler, 2002; Forman et al., 2003). As well as providing a habitat for wildlife, verges may also serve as a conduit for species movement for both generalist species that are tolerant of disturbance and ‘unwanted’ or invasive species spreading into the surrounding habitats. “The overall corridor function of infrastructure verges will most likely be influenced by the ecological contrast between the vegetation/structure in the corridor and the surrounding habitat” (Seiler, 2002; p 41).

2.3 Disturbance and edge effects

Disturbance and edge effects mainly result from pollution of the environment due to infrastructure construction and use. Physical disturbance appears during construction activities, when soil, relief and groundwater flows change, and alter the vegetation. In forested areas, the clearance of a road (i.e., the distance from the road to dense vegetation) changes microclimatic conditions up to 30 metres from the edge of this road (Mader, 1984). Hydrological impacts even may include a much longer distance. Chemical pollutants such as road dust, salt, heavy metals, fertilisers and toxins largely contribute to the disturbance and edge effects. Most of these pollutants accumulate in the close proximity of the infrastructure. Seiler (2002) mentions several studies observing direct effects on vegetation and animals at distances over several hundreds metres away.

Where tranquillity is perceived as an increasingly valuable resource (Gillen, 2003), traffic noise is one of the major polluting factors. It is questionable whether wildlife is similarly stressed by noise as humans. However, timid species might interpret traffic noise as an indicator of the presence of humans and consequently avoid noisy areas (Seiler, 2002). Seiler also mentions some studies on traffic noise avoidance for elk, caribou and brown bear. Birds appear to be especially sensitive to traffic noise. For The Netherlands, Reijnen et al. (1995) developed a simple model predicting the distance over which breeding bird populations of woodland birds and grassland birds might be affected by traffic noise. Their model is based on the observed relationship between noise burden and bird densities. In a Swedish study (Helldin and Seiler, 2003), however, these findings could not be verified. This study concluded that habitat changes as a consequence of road construction under some conditions could be more important than traffic noise.

2.4 Barrier effects

The barrier effect of infrastructure is the reduction of the number of animal movements crossing this infrastructure. It results from a combination of disturbance, avoidance effects (such as traffic noise, vehicle movement, pollution and human activity) and physical hindrances (such as the infrastructure surface, ditches and fences). The clearance of the infrastructure and the open verge character may also act as a barrier to many species, especially small ones (Oxley et al., 1974). Depending on the species, the number of successful crossings is a fraction of the number of attempted movements. Some species may not experience any physical or behavioural barrier at all, whereas others may not even approach the road (Seiler, 2002).

Most infrastructure barriers do not completely block animal movements, but reduce the number of crossings significantly (Mader, 1984; Merriam et al., 1989). “The fundamental question is this: how many successful crossings are needed to maintain habitat connectivity” (Seiler, 2002; p 45). To answer this question, knowledge is needed on (1) movements of specific species in a fragmented landscape, and (2) the chance on a successful road crossing for those species that actually cross the road.

2.5 Mortality

Despite millions of individual animals are killed on infrastructure each year, this traffic mortality is not considered as a severe threat to population survival for most common species (Seiler, 2002). In contrast to predation, traffic mortality is, however, non-compensatory and will kill a constant proportion of a population. Traffic mortality is, therefore, one of the major death causes for many species in human-dominated landscapes (Groot-Bruinderink and Hazebroek, 1996; Forman and Alexander, 1998; Philcox et al., 1999; Trombulak and Frissell, 2000). For some species, it is most likely responsible for regional extinction (e.g., badger Meles meles, Lankester et al., 1991; Clarke et al., 1998). Moreover, traffic is considered as one of the most important sources of mortality for many endangered or rare species. Although, the number of traffic victims may seriously reduce the population size of some species (Clarke et al., 1998; Huijser and Bergers, 2000), the effect of traffic mortality on populations is often difficult to measure as other factors, such as area, quality and spatial configuration of the habitat along the road, also play a role.

There are complex relationships between the barrier effect and the mortality effect, which determine mortality during movement (i.e., the movement death rate), and the number of successful crossings (i.e., the crossover rate) (Verboom, 1994, see Figure 2). To quantify these effects, relationships between traffic and road characteristics must be found. For instance, a wider road encourages both higher traffic volumes and speeds. This, in turn, reduces the chance of a successful road crossing (as formulated by Van Langevelde and Jaarsma, 2004), as the intervals between vehicles become much smaller. Moreover, the wider the road, the more time an animal needs to cross the road and the less chance it has to actual succeed. In addition, an increase of volume may lead to such a flow of vehicles that individuals are restrained to cross the road. Finally, an increase of volume also determines the noise level increasing the barrier effect. In the next section, we focus on the mortality effect as current knowledge does not allow quantifying the barrier effect of roads (see Verboom, 1994).

3. MODELING TRAVERSING WILDLIFE

3.1 Relevant road, traffic, vehicle and species characteristics

What are the relevant road, traffic, vehicle and species characteristics that have an effect on the traversability? Regarding the road characteristics, it is clear that as the road is wider, animal need more time to cross and the probability of successful road crossings decrease. Moreover, wider roads carry higher traffic volumes and allow for higher speeds. A small clearance of a road has a negative impact on the traversability of the road (Oxley et al., 1974; Adams and Geis, 1983; Clevenger et al., 2003). A small clearance can often be found in forested landscapes.

High traffic volumes cause high noise loads and a high collision probability, as the intervals to cross between the vehicles are small. An increase of traffic volume may lead to such a flow of vehicles that individuals do not cross the road anymore. Traffic volume may, however, largely fluctuate over the day and between seasons.

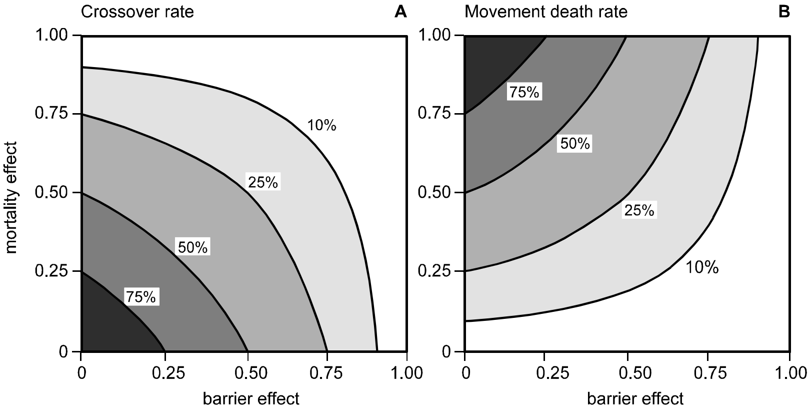

Figure 2. (A) The crossover rate and (B) the movement death rate as function of the barrier effect and the mortality effect (Verboom, 1994).

The traffic volume that largely determines traffic mortality (called the decisive traffic volume) depends on the time split of the daily traffic flow and the activity period of the animals during the day. The daily traffic pattern has characteristic peaks in the rush hours (7% in the morning and 10% in the afternoon) and an intermediate level during the evening (about 5%). During the night hours, only 1 or 2% of daily volumes passes. As animals are active during dusk and night, they deal with considerably lower hourly volumes than during daylight time. Moreover, most animals only cross a road when traffic volume is rather low, which is the case during dusk and night (Clevenger et al., 2003). With respect to vehicle characteristics, their size (length and width) and speed affects the traversability. Vehicle speed seems to be important because of the better opportunities for both animal and driver to avoid a collision when the vehicle speed is lower.

Depending on the road, traffic and vehicle characteristics, different animal species experience differences in traffic mortality, such as in insects (Munguira and Thomas, 1992; Vermeulen, 1994), reptiles and amphibians (Hels and Buchwald, 2001), birds (Clevenger et al., 2003) and mammals (Mader, 1984; Lankester et al., 1991; Clarke et al., 1998). Whether species are vulnerable to traffic mortality depends on characteristics such as their home range size, the period of the day or season during which the animals are active, whether they move large distances during foraging, dispersal or migration, their traversing behaviour (velocity, reaction to approaching vehicles), their body length or the size of the group in which the individuals move. Species of closed and half-open landscapes with a large home range that move large distances are relatively sensitive to traffic mortality since they frequently cross roads that have a low clearance (e.g., Oxley et al., 1974; Adams and Geis, 1983; Groot Bruinderink and Hazebroek, 1996; Clarke et al., 1998). Fast moving mammals (often large animals) are less vulnerable for traffic mortality. However, these animals often have relatively large home ranges or move large distances. For these animals, the effect of traffic mortality on population dynamics can only be assessed when their daily and seasonal road crossings are considered.

3.2 Traffic flow theory

In traffic engineering, the calculation of headway distributions, i.e., the frequency of the length of gaps between successive vehicles in a traffic flow at a given cross-section is commonly based on the assumption of a Poisson distributed process (Haight, 1963, 1966; Drew, 1968; Leutzbach, 1988; Daganzo, 1997). The Poisson distribution is a discrete distribution that describes the number of events during a given time period. Here, the event is a vehicle arriving at a given location. The numbers of events in sequential time periods of an equal length are independent stochastic drawings. For a given traffic volume, the probability of a certain number of arrivals within a fixed time period depends only on the length of this period and is thus constant for periods of equal length. When the number of vehicles in a sequence of fixed time periods is Poisson distributed, their headways are (negatively) exponentially distributed, and independent of each other. To be Poisson distributed, it is necessary that the vehicles approach a certain location without any disturbance, due to for example traffic lights. Also, the traffic volumes should be not too high: say, below 400 to 1000 vehicles h^{-1}.

According to the Poisson distribution, the probability *P(x)* that *x* vehicles arrive at a given location on a one-way road in time period *T* (in s) can be described as

$$P(x) = \frac{(\lambda T)^x e^{-\lambda T}}{x!} \qquad (1)$$

where λ is the traffic volume in vehicles s^{-1}. For a successful traversing, x should be equal to 0 during at least the time period T when the animal "occupies" the road for traversing. For $x = 0$, equation (1) changes into

$$P(0) = \Pr\{\text{Headway} > T\} = e^{-\lambda T} \qquad (2)$$

In other words, $P(0)$ is the probability that the front of the next car does not arrive within a period of T seconds, given a traffic flow with on average λ vehicles s^{-1}. The relevant length of the time period T depends on road, traffic, vehicle and species characteristics as mentioned above.

When the road carries traffic in two directions, with flows λ_1 and λ_2, then both flows can be described as a Poisson process. The well known mathematical theory learns that the two-way flow on that road, $\lambda = \lambda_1 + \lambda_2$, is also a Poisson process. So formula (2) remains the same in this situation, with λ now representing the two-way traffic volume.

3.3 Formulation of the traversability model

For the application of headway distributions of traffic flows to traversing animal species, several assumptions are made (Van Langevelde and Jaarsma, 2004). The main difference in road crossing by people and animals is that most people can reasonably estimate whether a gap between two successive vehicles is sufficiently large to cross safely. As the strategies used by animals to traverse roads are unknown, it is assumed that they act “blind”, without responding to the presence of a car, if any, and maintain a constant speed during their traverse. Especially in situations with a low clearance, the “blind” traversing is a realistic supposition. Beside the animal, we further presume that also the driver is ‘blind’, because the time available to avoid a collision with a traversing animal is around 1 second or less. So the traversability model does not include “corrections” by human and/or animal when their presence coincides. Two further assumptions for modelling are: (1) when an animal during its movement through the landscape finds a road on its way, it will traverse this road promptly, with a constant speed and at an angle ($\pi/2 - \alpha$) with the road axis (for $\alpha = 0$ the crossing is perpendicular), and (2) the traversing animal will be killed in a collision if the appearing gap in the traffic flow at the start of its traversing is too small, and, in reverse, there is a successful traverse if the gap is at least as large as the animal needs for its traverse.

We distinguished two chances for a collision that determine the traversability: a collision can appear (1) when the animal is on the part of the road used by the car, and (2) when the animal hits the side of a car (Jaarsma et al., in prep.). Distinguishing these two chances for a collision, the period δ_1 (in s), during which the car hits the animal, is

$$\delta_1 = \frac{\dfrac{W_c}{\cos(\alpha)} + L_\mathrm{a}}{V_\mathrm{a}} \qquad (3)$$

where W_c is car’s width (in m), and L_a and V_a are the animal’s length (in m) and speed (in m s^{-1}) respectively. We assume here for reasons of simplicity that car and animal can be represented by a rectangle. For $\alpha = 0$, *i.e.*, perpendicular traversing, formula (3) reduces to

$$\delta_1 = \frac{W_c + L_a}{V_a} \qquad (4)$$

So, if the animal traverses the road at an arbitrary moment, it can survive if the front of the next car does not arrive within a period of δ_1 seconds. The probability of this event, P_1, is (see formula 2)

$$P_1 = \Pr\{\text{Headway} > \delta_1\} = e^{-\lambda\delta_1} \quad (5)$$

The period δ_2 (in s) during which the animal can hit the car is

$$\delta_2 = \frac{L_c + W_a \cos(\alpha)}{V_c} \quad (6)$$

where W_a is animal’s width (in m) and L_c and V_c are the car’s length (in m) and speed (in m s^{-1}), respectively. So, if the animal traverses the road at an arbitrary moment, it will not hit a car and can survive if the front of the last car has passed at least a period of δ_2 seconds ago. The probability of this event, P_2, is

$$P_2 = \Pr\{\text{Headway} > \delta_2\} = e^{-\lambda\delta_2} \qquad (7)$$

Combining both events, the animal can traverse without a collision with probability P_a that equals the product of formulae (5) and (7)

$$P_a = e^{-\lambda\delta_1} e^{-\lambda\delta_2} = e^{-\lambda(\delta_1+\delta_2)} \quad (8)$$

Expressed in the characteristics of animal and car this formula transfers into

$$P_a = e^{-\lambda\left(\frac{\frac{W_c}{\cos(\alpha)}+L_a}{V_a}+\frac{L_c+W_a\cos(\alpha)}{V_c}\right)} \quad (9)$$

For the perpendicular traversing, α = 0 and formula (9) reduces to

$$P_a = e^{-\lambda\left(\frac{W_c+L_a}{V_a}+\frac{L_c+W_a}{V_c}\right)} \quad (10)$$

Based on formula (10), the number of traffic victims of a species *a*, D_a, during time period τ can be estimated by

$$D_a = (1-P_a)K_{a,\tau} \quad (11)$$

where $K_{a,\tau}$ is the number of attempts to traverse the road by individuals of species *a* during the time period τ. The parameter $K_{a,\tau}$ is, however, difficult to measure and depends on several species and landscape characteristics such as home-range size, movement behaviour during foraging or dispersal, road density and the location of the road with respect to, for example, the foraging areas. We therefore suggest the model *not* to apply to calculate the *absolute* number of traffic kills of species *a* during, say, a season, but to use it in a relative way. The traffic mortality can be estimated for two situations with the same number of attempts to traverse the road. For example, the present situation is compared with the planned situation with new road and traffic characteristics and the difference between both is considered to be the difference in impact.

4. APPLICATION OF THE TRAVERSABILITY MODEL

4.1 Integral strategy of Traffic-calmed Areas

In order to prevent habitat fragmentation due to infrastructure, mitigating interventions can be applied. These interventions can be directed towards enhancement of the traversability of the roads themselves (decreasing traffic intensity and/or speed), creating wildlife overpasses or underpasses, reducing mortality chance (fences), or quality enhancement of the adjacent habitat (noise reducing walls). However, the applicability of these interventions differs between types of roads. We distinguish here three types of roads by their function (Jaarsma, 1997): (1) motorways, with mainly a flow function that offers fast and comfortable service for through traffic on long distances, (2) rural highways, with an access function for regions and for opening up regions, and (3) minor roads, with mainly local collector and access roads with mixed traffic for destination accessibility.

Mitigation measures for major roads (motorways and highways) will not be as effective for minor roads as (Van Langevelde et al., in prep.):

1. Minor roads have a diffuse victim pattern: many locations with low frequency of accidents. This makes the designation of bottlenecks problematic.

2. These bottlenecks are not only more difficult to designate, also prioritising of interventions is much more complex as many accident locations can be a bottleneck.

3. Interventions for rural highways or motorways are primary directed towards reduction of the barrier effect (without increasing traffic mortality). However, interventions for minor roads should primarily reduce the number of accidents, without increasing the barrier effect.

4. Enhancement of the traversibility of the road itself would more feasible for a minor road than for rural highways or motorways, such as speed limiting interventions and/or temporary closure for vehicles. A condition for such interventions would be the presence of acceptable alternatives for through traffic.

5. A large problem with interventions for minor roads is the lack of specified knowledge. There is much more knowledge on the effects of rural highways and motorways on fauna. We assume this coincides with the difficulty to determine the effects of minor roads.

Locations with high victim numbers are generally first nominated for mitigating measures. This is indeed frequently applied to rural highways and motorways (Forman et al., 2003; Van Bohemen, 2005). For minor roads, however, even when such locations with relatively high accident frequencies occur, the low number of victims and the low accident risk result in an (too) important role of coincidence. Therefore, such a method is for minor rural roads not feasible to determine bottlenecks or enhancement after mitigation.

Interventions to prevent habitat fragmentation by infrastructure can only be really successful when problems concerning minor roads are also accounted for, because:

1. As soon as interventions are implemented on one road section in a road network, unexpected effects can occur elsewhere. This applies to animals (alterations in movement patterns) and human (alterations of traffic flows). For example, measures on one specific road section can have consequences for other road sections in the network, either positive or negative, because of the hierarchy within the road network, consisting of interconnected networks of motorways, highways and minor roads.

2. A shift can be expected as the number of traffic victims on minor roads will increase when mitigating interventions on rural highways and motorways are implemented. The home range of a lot of species covers more than only one road. Within this context, it is stressed that a lot of species not only live in nature reserves but also in other rural parts of the landscape.

3. Implementing road design or road closing interventions for a certain road section is only possible when alternatives are offered to through traffic. For offering alternatives, rural highways and motorways can play an important role.

These effects can be prevented, not by planning based on separated road sections (the ‘road section approach’), but by planning based on a coherent road network (the 'network approach'; Jaarsma, 1997, 1999, 2004; Van Langevelde and Jaarsma, 1997). Therefore, we recommend an integral strategy, in which the problems concerning habitat fragmentation on minor roads, rural highways and motorways in a region are all accounted for in mutual cohesion (Jaarsma and Willems, 2002a; Van Langevelde et al., in prep.). Such an integral strategy requires a regional approach, say, between 50 and 200 km^2, and not on the level of only one or a few specific road section(s). The planning concept "traffic-calmed rural areas" (Jaarsma, 1997) is based on such regional network approach. This concept is originally developed to promote traffic safety and tackle rat-run traffic in rural areas. We argue here that this concept can also be applied to mitigate habitat fragmentation.

4.2 Planning concept "traffic-calmed areas"

During the 1970s, the concept of urban residential traffic-calmed areas was developed. These residential precincts are areas within urban areas with restricted rights for motorised traffic. This is expressed in a specific design, directed to a low speed level. This concept has already served as an international model (Macpherson, 1993). The concept of "traffic-calmed rural areas" uses the same ideas derived from built-up areas and transfer them to the rural area (Jaarsma, 1997). The underlying idea is a clear separation between space for living that involves inhabitants and recreationists as well as wildlife, and space for traffic flows. Then, starting positions for (re)designing roads in traffic-calmed areas are the preferred functions and not the appearing traffic flows. Usually, residential functions (inhabitants, recreationists, wildlife) will be emphasised, and not the traffic function for through traffic.

Traffic-calmed areas will be accessible by means of minor roads with a moderate (technical) design for low speeds and low traffic volume. Through traffic will find faster alternative routes over rural highways or motorways. On these roads, which additionally give access to the traffic-calmed area, bundled traffic flows appear (Jaarsma, 1997). Reduction of traffic speed and volume due to the bundling of traffic flows will have a positive impact on the traffic safety. Bundling also favours noise load. Opposite to small increases along roads with increased traffic flows, large reduction of noise load occurs along traffic-calmed roads. The most important disadvantage of the traffic-calmed areas is the increase in vehicle mileage because the route along minor roads is often shorter in both length and time than the functional route along motorways and other major roads. In time, however, calculated differences mostly are very small (Jaarsma, 1997; Jaarsma and Willems, 2002a).

From explorative research (Jaarsma and Van Langevelde, 1997; Jaarsma and Willems, 2002a and 2002b), it seemed that profit for nature is gained by "overall" decrease of zones with high noise loads and enhanced traversibility, especially for larger mammals. Based on model calculations, a decrease of traffic intensity seems to have the largest impact on road crossings by fauna. With that, the traffic-calmed areas create opportunities for local populations with fewer limitations for exchange.

4.3 Gerdyksterwei as case study

We applied the concept traffic-calmed areas and the traversability model to several regions where bottlenecks appear between wildlife and the road network to compare alternative network solutions and their impacts on traversability for wildlife (e.g., Jaarsma and Van Langevelde, 1997; Jaarsma and Willems, 2002a). Here, we present an example of a former section of the Dutch national road network, the Gerdyksterwei between the Frisian villages Gorredijk and Beetsterzwaag, which is bypassed today by the A7 motorway (Figure 3).

Since the A7 motorway is in service, carrying daily about 30,000 motor vehicles, the Gerdyksterwei is intended to be a minor road with modest traffic flows. However, many drivers between Gorredijk and the nearby town of Drachten still prefer the former route above the functional route along the A7. Therefore, daily volumes on the Gerdyksterwei (4,100) and in the center of the village of Beetsterzwaag (5,300) are too high from an environmental point of view. By autonomous developments, these volumes are even expected to increase with a further 1,000 vehicles per day in the next ten years. Although the technical capacity of the Gerdyksterwei is large enough to handle these volumes (the road still has its traditional layout with a broad pavement, based on its former function in the national network), the present volume forces two problems. Within the village of Beetsterzwaag livability of the inhabitants is threatened, and in the rural area the Gerdyksterwei intersects an extended wooded area with a lowland brook (Koningsdiep), which is a core area in the Dutch National Ecological Network. Here, for small and larger mammal species such as hedgehog (*Erinaceus europaeus),* rabbit (*Oryctolagus cuniculus*), roe deer (*Capreolus capreolus*), and (when re-introduced) otter (*Lutra lutra*), the collision chance when traversing the Gerdyksterwei is considerable by its high traffic volumes. Therefore, the local government investigated the impacts of rural traffic calming for livability and wildlife movement. Within this context, traffic calming means priority being given to nature (in the rural area) and to people (in the village), not to through traffic. The latter is offered an alternative route with a high quality via the A7 motorway. Wildlife can traverse this motorway safely through underpasses. As a consequence of traffic calming, speeds and/or volumes on the Gerdyksterwei must decrease, contrary to the autonomous development.

We elaborate 4 levels of traffic calming: (1) mainly legal measures, including a rigid enforcement of the present speed limit of 80 km h^{-1}; (2) implementation of a so-called rural residential area with a legal speed limit of 60 km h^{-1} and with a few speed humps; (3) the previous, with more measures to reduce speed and in combination with a reduction of the pavement width; (4) the previous, with limited access: between 7 p.m. and 7 a.m. access for local residents only. By these measures, the estimated effective speed on the Gerdyksterwei decreases. Consequently, an increasing part of the through traffic will take the A7 because it offers a faster or at least more comfortable route than the traffic-calmed Gerdyksterwei. Based on travel times between Gorredijk and Drachten, it is estimated that the first level of traffic calming only slightly reduces the future flows.

The implementation of a rural residential area will be more effective in avoiding through traffic. The level with limited access reduces the volumes between 7 p.m. and 7 a.m. from 400 to approximately 100, which means on average only 8 vehicles h^{-1}.

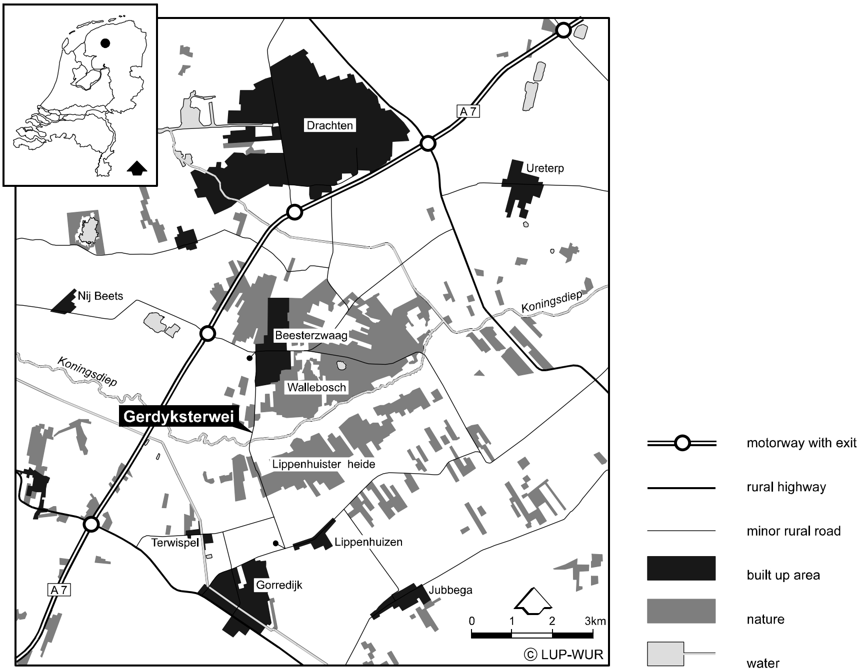

Figure 3. The Gerdyksterwei in its regional context. This road traverses both the dry and the wet National Ecological Netwerk (the Wallebosch and Lippenhuisterheide and the low land brook Koningsdiep, respectively). Despite the presence of the A7 motorway, the Gerdyksterwei still carries a lot of cars travelling from Gorredijk to Drachten and further to the north v.v. The village of Beetsterzwaag also burdens a large part of this traffic flow (elaborated from Jaarsma and Van Langevelde, 1997).

This extra reduction during the night is relevant considering the ecology of the mammals mentioned above, because their decisive period for movement is during the night. Nightly volumes for the other situations are estimated by the assumption that one quarter of the daily flow appears between 7 p.m. and 7 a.m., which is equally spread over these twelve hours. Table 1 presents an overview of the road and traffic characteristics applied into our calculations. The decisive traffic volumes in the table are the average hourly volumes during the night.

The impacts of traffic calming on wildlife traversability for the Gerdyksterwei are presented in table 2, showing the resulting changes in traffic mortality per 10^4 traversings for the roe deer, the otter, the rabbit and the hedgehog. From table 2, we conclude that traffic calming can be an effective method to improve traversability for wildlife. Differences between the 4 species are small, however, the small and slow moving hedgehog has a somewhat higher victim reduction.

Table 1. Road and traffic characteristics for the Gerdyksterwei in the actual situation and estimated for the autonomous development and the 4 levels of traffic calming (explained in the text).

Characteristic	Present situation	Autonomous development	Levels of rural traffic calming			
			Level 1	Level 2	Level 3	Level 4
Pavement width (m)*	7	7	7	7	5	5
Legal speed limit (km h^{-1})	80	80	80	60	60	60
Estimated effective speed (km h^{-1})	85	80	72	60	50	50
Average annual daily volume (vehicles d^{-1})	4,200	5,200	4,500	2,500	1,600	1,300
Decisive volume (vehicles h^{-1})	84	104	90	50	32	8

* *pavement width is not included in formula (10), but it affects both effective speed and traffic volume*

The table also clearly shows that, if traversability is already considered as an ecological problem in the present situation, measures must be taken since in the autonomous development the situation will worsen. Compared to the autonomous situation, the first level of traffic calming shows a slight improvement of the traversability, but this is still worse than in the present situation. A further development of measures allows for a considerable improvement: the second and the third calming levels show a reduction of traffic kills of about one third and more than 50%, respectively. In this situation, with wildlife movements during the night as decisive period, a total closure for through traffic during the night as in level 4 is very effective. It reduces the number of traffic kills to about 10% of the present value.

5. SYNTHESIS

In this chapter, we show the important, but not always distinguished, role of major as well as minor roads and their traffic flows on wildlife, as a part of their environmental impacts. For a generation already, the road network pervades a paradoxical role in our society. On the one hand, people seek to harvest the benefits of an expanding road system, including an improving access to ‘green’ areas. On the other hand, people have growing concerns about threats of roads to the natural environment, including noise, emissions, vehicular-related air quality and loss of species and wildlife habitat.

Table 2. Estimated victims per species for the Gerdyksterwei in the present situation, the autonomous development and the 4 levels of traffic calming (explained in the text). Victims relative to the present situation with a decisive volume of 84 vehicles h^{-1}

Animal species	Kills per 10^4 traverses in present situation (= 100%)	Relative kills per 10^4 traverses (%)				
		Autonomous development	Level 1	Level 2	Level 3	Level 4
Roe deer	204	125	112	66	45	11
Otter	184	126	112	66	46	11
Rabbit	162	126	113	67	46	12
Hedgehog	572	124	109	62	41	10

Originally, the road network was built in an era when transportation planners focused on providing safe and efficient transport with little regard for wildlife. “That is changing. … the call for new knowledge and skills is stronger than ever” (Forman et al., 2003; p xiii).

Also new legislation, such as the EU Habitat Directive, enforces the transportation community to include ecological impacts into their planning system. More specifically, for relevant (threatened) species in the region the impacts of measures proposed in a transportation plan must be described (Haq, 1997; Iuel et al., 2003). Wildlife traversing a road is an important aspect of habitat fragmentation by infrastructure and its traffic flows. So far, a tool is missing to estimate the impacts on wildlife movements of changes in a regional road network and/or the layout of specific road sections and the resulting changes in traffic volumes and speeds. The traversibility model, as presented in this chapter, enables to include impacts of roads and their traffic flows on wildlife movement and traffic kills among animals.

The traversability model can contribute to the conscious integration of nature and engineering in a way that is useful for both human and nature (Van Bohemen, 2005). This model can be used to estimate the changes in traffic mortality for animal species as a result of changes in road and traffic characteristics, by comparing changes in road or traffic characteristics or alternatives for road design and traffic volumes. Then, the model can provide insight in the relative effects of these road and traffic characteristics on population dynamics of wildlife. When data on traffic mortality are available (Groot Bruinderink and Hazebroek, 1996; Garrett and Conway, 1999), the model could be used to predict changes after applying mitigating measures. When numbers of victims are not available, however, model predictions based on road and traffic characteristics and the distribution and size of the local populations of the species could also be useful to determine the locations where mitigating measures should be applied. It offers thus a relatively simple addition to the existing toolbox of the planner and it only asks for limited data.

So far, the traversability model is not tested in experiments. For such an experiment, among others, reliable numbers of road crossing by individual animals as well as numbers of traffic kills per road section should be gathered. As far as we know, there are no studies on the former. Some studies provide numbers of victims, but due to scavengers or identification problems, especially for small animals, the actual numbers are difficult to measure. This conclusion already holds for seventy years (Stoner, 1936; Hels and Buchwald, 2001; Slater, 2002). It is therefore questionable whether an empirical experiment can provide reliable data for the validation of the absolute numbers of traffic kills as calculated by the model. When the model is used to calculate the relative difference between two situations with different road and/or traffic characteristics, systematic errors in the model by animal behavior, if any, will be eliminated by subtraction.

The traversability model is based on a limited number of road, traffic, vehicle and species characteristics. Other characteristics also influence the road crossing, such as road lighting as some animals avoid these roads, whereas others are attracted. Some species will flee or stay when a vehicle is approaching, e.g., the traversing speed will be underestimated when individuals flee. Moreover, some animals restrain from roads when traffic volume increases. We assumed that animals cross roads without any waiting time. This may be valid for landscapes where the clearance is low, but otherwise it is plausible that animals are restrained to cross when a vehicle is approaching. They may also be restrained when traffic volume is high due to the constant noise and visibility of vehicles. Moreover, we assumed that when an animal and a vehicle are at the same location at the same moment, a collision occurs. This might not be true since corrections by humans and animals and also mis-hits where the animal survives a collision (e.g., because they are small enough to survive between the tires of a vehicle) also affect traffic mortality. So far, the assumptions in the traversability model exclude the above-mentioned factors. Relaxing these different assumptions does, however, not drastically change the model but have an effect on the predicted traffic mortality.

Environmental impacts of infrastructure such as noise and pollution are estimated with quantitative models. Except for habitat loss, the impacts on nature are difficult to quantify. Maybe that is the reason that, beside large-scale mitigation measures by means of wildlife underpasses and overpasses, there is a lack of attention for impacts on wildlife so far. To bridge this gap, and to enable transportation planning to include the impacts on wildlife in the planning process for a regional road network, the presented traversability model can be subservient. This is illustrated in the case study, where several levels of traffic calming are compared with the autonomous development. We show that traffic calming can drastically reduce traffic mortality. Such a traversability model could thus be a tool for transportation planners and conservationists to prevent traffic accidents and protect biodiversity.

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