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Effects of scale and efficiency of rural traffic calming on safety, accessibility and wildlife

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A R T I C L E I N F O

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A B S T R A C T

This paper examines the effects of scale and efficiency of regional traffic calming on traffic safety, rural accessibility, and survival of wildlife. We distinguish by the scale of road networks affected and considered the efficiencies of various bundling of traffic flows on designated routes. Safety gains are smaller for larger scales systems of traffic bundling and, given a particular scale of traffic calming, considerably lower with less efficient bundling. Efficient traffic bundled on higher speed, major roads results in a small gains in travel time and safety, but the presence of wildlife increases more with larger scales of traffic calming.

1. Introduction

In rural areas, both traffic safety issues and protection of biodiversity are important elements in transportation policy, but work combining the two elements is limited. At times, however, there are efforts in regional rural traffic-calming schemes to improve road safety as well as to reduce vehicle-wildlife collisions (Jaarsma and Willems, 2002). Questions remain, however, concerning the combined impact of level of traffic calming and its efficiency on traffic safety, rural accessibility, and survival of wildlife. We investigate these questions by looking at the number of grid cells combined in a traffic-calmed area, and the efficiency with which former diffuse flows of through traffic are bundled on major roads.

2. Modeling flows in a rural road network

We initially define a network of minor roads in a regular square grid of width L in an infinite area (Fig. 1a). All the roads have the same mixed function serving local access and longer distances trips. They also have similar characteristics, for example in terms of pavement width, and traffic volume. The area is the usual rural landscape and includes villages and other concentrated human settlements, agricultural land, businesses, recreational facilities, and natural areas. Motorways as well as larger towns and cities are excluded from the area. The human population density is B people/km^2 in both the nodes of the road network and in the grid cells enclosed by this network. For simplicity, we consider only car traffic, and assume that all flows originate from the nodes.

Traffic generation depends on the number of people and the distances travelled daily by car per capita, G km/day with an equal number of people traveling in each node. In this infinite network, every node serves four neighboring grid cells with every grid cell consisting of four nodes. The number of people who start traveling in a node can be estimated by multiplying the density of the human population, B, in the grid cell with its area, L^2. The daily vehicle km generated in a node, F, is then $F = BL^2G$. The distribution over the network F starts from each node and goes in four directions. Because we assume an

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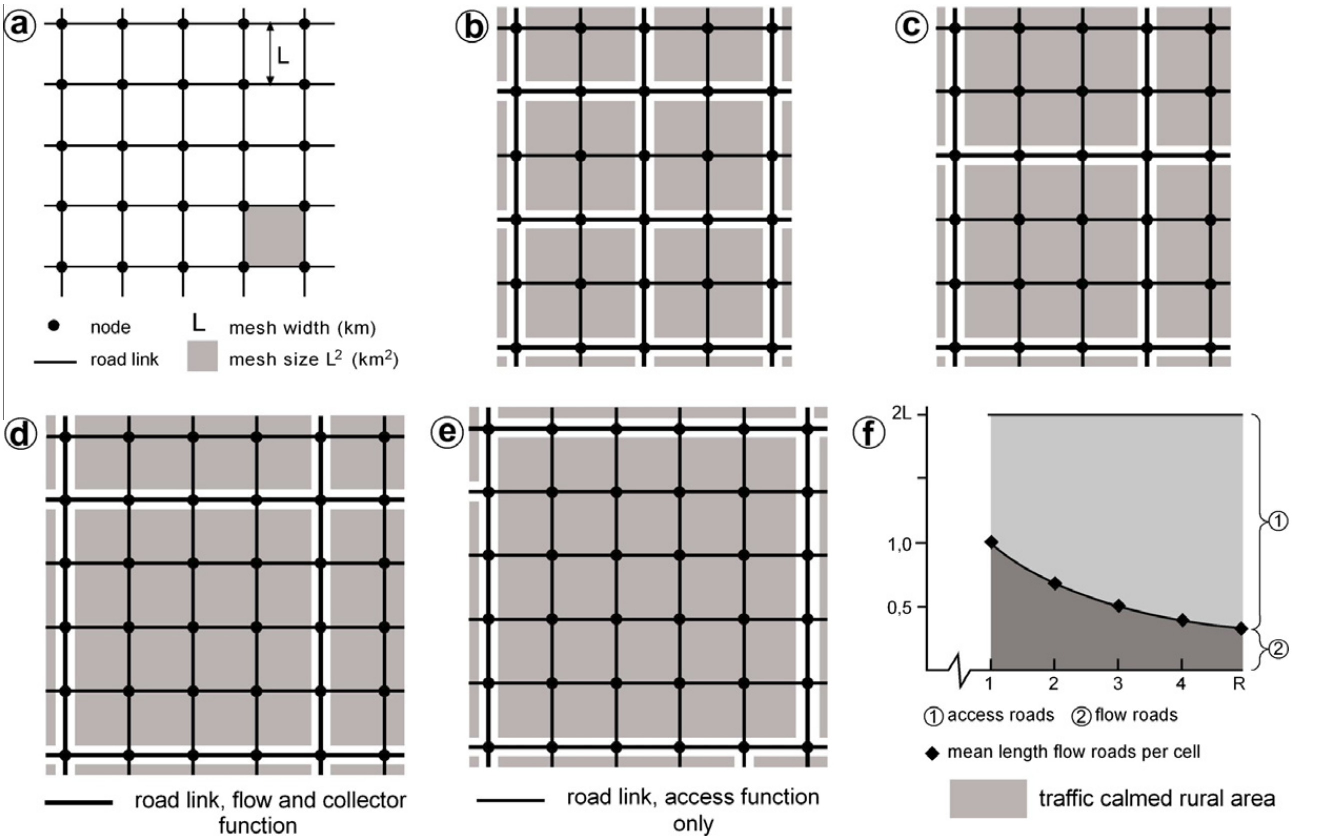

Fig. 1. Rural road networks in a regular square grid: (a) minor roads with nodes and road links with a length of L km; (b–e) two types of roads and sizes of the traffic-calmed areas; (f) the changing proportion of roads with access and flow function within the road length per grid cell ($2L$) as function of the different sizes of the traffic-calmed area, as presented in (b) to (e).

infinite network, and the same traffic volume on each road link, all destinations are found in the four adjacent nodes and not further away, regardless of how far people travel. So, all road links starting at any node carry $0.25F$ vehicle km/day from that node. However, every road link also carries traffic from its two adjacent nodes, and therefore, the two-directional flow on every road link is twice this amount: $0.5F$ vehicle km/day. Using this estimate, we can derive the traffic volume λ (vehicles/day) by dividing the number of vehicle km/day by the length of the road link: $\lambda = 0.5F/L$. Based on the average statistics for rural areas in the Netherlands (Van Langevelde et al., 2009), B is about 200 inhabitants/km^2, G about 16 vehicle km/day per capita, and L is 1.11 km. The daily vehicle km generated in a node, F, is then about 4000 vehicle km/day. Consequently, the traffic volume λ for the area with similar roads and an evenly distributed human population is 1800 vehicles/day.

We distinguish between minor roads with primarily a local access function, situated within the traffic-calmed area and from which the traffic can quickly flow to surrounding major roads with primarily a flow function (Fig. 1b–e). Roads for access function will have a much lower traffic volume than roads with a flow function (Jaarsma, 1997). The efficiency of a volume reduction on access roads compared with the uniform network with diffuse flows in Fig. 1a is represented by γ, indicating the fraction of the original daily volume that is expected to remain on a road with an access function only.

$$\lambda_a = \gamma\lambda \tag{1}$$

For lower values of γ, a larger proportion of traffic will use the flow roads and hence the degree of bundling as well as the traffic calming are more efficient.

The size of traffic-calmed areas is $(SL)^2$ where S is a scale coefficient for the size of the traffic-calmed area (S is two in Fig. 1b, rising to five in Fig. 1e); represents the number of grid cells in the horizontal or vertical direction in a traffic-calmed area. $S = 1$ thus represents diffuse flows without traffic calming (Fig. 1a). In Fig. 1b–e, 4, 12, 24 and 40 roads have access functions within a traffic-calmed area and, consequently, a reduced volume λ_a. In general, this number is $2S(S-1)$ with a length of $2S(S-1)L$. If the amount of daily vehicle km is constant, roads surrounding traffic-calmed areas have to carry extra traffic volume because the bundling of traffic on these roads. In our network, the number of roads with a flow function per traffic-calmed area is $4S$ with a length of $4SL$. However, because these roads also serve the neighboring grid cell, the effective length is halved to avoid double counting the traffic volume, hence $2SL$. To calculate the extra volume on roads with a flow function, we use the ratio of the number of roads with an access function to the number with a flow function. This ratio is estimated as $(2S(S-1))/(2S) = S-1$. The proportion between access and flow roads for the road length per grid cell, $2L$, changes as the function of the scale coefficient S: the larger the traffic-calmed area, the higher the proportion of access roads (Fig. 1f). With four cells (Fig. 1b), the length of access roads equals the length of flow roads. With nine cells (Fig. 1c), the proportion is 12:6, or, given the length per cell of 2L, 1.33:0.67. For 25 cells (Fig. 1e) this changes into 1.6:0.4.

The additional traffic on roads with a flow function is because of switching vehicles that previously used the roads with an access function in the traffic-calmed areas. The extra daily volume of $(1-\gamma)\lambda$ for each road that now has an access function in the traffic-calmed area is added in equal proportions to the existing traffic volume on the roads with a flow function; giving an extra volume on the latter roads of $(1-\gamma)\lambda(S-1)$. The daily traffic on roads with a flow function thus becomes:

$$\lambda_f = (1 + (1-\gamma)(S-1))\lambda \tag{2}$$

Results for the increasing coverage of traffic-calming in the imaginary area for road length, number of grid cells, and volumes calculated with $\gamma = 0.1$, are summarized in Table 1.

3. Modeled impacts of traffic calming

3.1. Traffic safety

Roads differ in their safety levels. Dutch data show that accident risks on local roads are roughly twice those on major, arterial highways: 0.031–0.014 fatalities per 10^6 motor vehicle km (CROW, 2002). Consequently, concentrating traffic on major roads will reduce fatalities on minor ones. The impact of traffic calming can be calculated by comparing the numbers of vehicle km travelled on access and flow roads, $L\lambda$, using the indices a and f, and then multiplying these by their specific fatality risk, I_a or I_f (0.031 or 0.014), for different levels of traffic calming. For the initial situation, fatalities per grid cell, O (number/day), is

$$O = 2L\lambda I_a \tag{3}$$

For situations with different levels of traffic calming, we distinguish between traffic flows on roads with an access function and those with a flow function. Using the road lengths and volumes from Table 1 for level (1) with $S = 2$ of traffic calming involving four grid cells, the number of fatalities per grid cell, $O^{(1)}$ is

$$O^{(1)} = \frac{((4L\gamma\lambda I_a) + (4L(1 + (1-\gamma))\lambda I_f))}{4} \tag{4}$$

The generalized equation for level (n) becomes

$$O^{(n)} = \frac{((2n(n-1)L\gamma\lambda I_a) + (2nL(1 + (1-\gamma)(n-1))\lambda I_f))}{n^2} \tag{5}$$

We expressed the outcome of this relative to the results for the road network with diffuse flows and no traffic calming as a function of the levels of calming (S) and degrees of effectiveness (γ). The horizontal dotted line in Fig. 2 indicates the theoretical maximum level of safety for situations where all roads have the accident risk of a flow road. Using the ration 0.014:0.031, this theoretical level is 45, i.e. a reduction of 55% in the number of traffic victims, compared to a situation where the road network has diffuse flows and no traffic calming. However, the models for rural traffic calming, Fig. 1b–e, shows that some rural traffic flow still use access roads in a traffic-calmed situation and so the gains in safety will be somewhat smaller. In short, as the scale of the traffic calming increases, the gains in safety will decrease because a large proportion of the roads are classified as access roads, as illustrated in Fig. 1f. Gains are considerable, however, even for the highest level of traffic calming, especially when the efficiency of traffic calming is high. The lower the value, the more the original traffic is bundled on flow roads.

Table 1
Road and network characteristics for a regular square grid with a length of L km and different levels of traffic calming. *Source*: Van Langevelde and Jaarsma (2009).

Variable	Initial network	Level (1)	Level (2)	Level (3)	Level (4)	Level $(n-1)$
Scale factor S	1	2	3	4	5	n
Length of roads with flow function (f) on each side of the traffic-calmed area	L	$2L$	$3L$	$4L$	$5L$	nL
Grid cells in traffic-calmed area	–	4	9	16	25	n^2
Length of roads with flow function (f)[a]	$2L$	$4L$	$6L$	$8L$	$10L$	$4nL/2 = 2nL$
Length of roads with access function (a)	0	$4L$	$12L$	$24L$	$40L$	$2n(n-1)L$
Volume on access roads λ_a [b]	λ[c]	0.1λ	0.1λ	0.1λ	0.1λ	$\gamma\lambda$
Volume on flow roads λ_f [d]	λ	1.9λ	2.8λ	3.7λ	4.6λ	$(1 + (1-\gamma)(S-1))\lambda$

[a] The actual number is halved because all roads surrounding the grid cells also serve its adjacent grid cells.
[b] $\gamma = 0.1$.
[c] All roads have both a flow and access function.
[d] Roads with a flow function also serve the local access of adjacent grid cells.

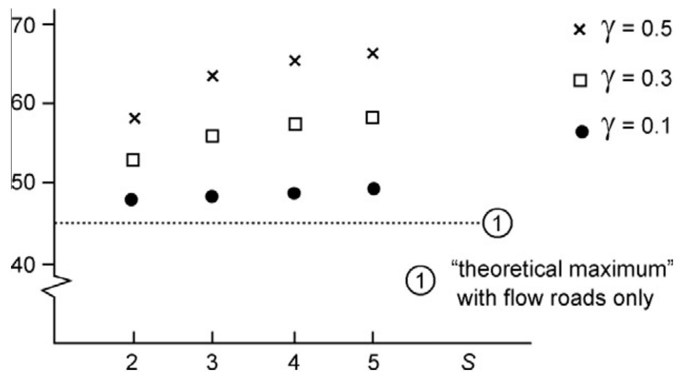

Fig. 2. The relative number of fatalities for four scales of traffic calming and for three levels of effectiveness compared to the initial road network.

3.2. Travel times and accessibility

The impact of traffic calming on travel times results from drivers reacting to the new technical design for the various road categories and different speed limits; the limit is 80 km/h for arterial highways (V_f) and for minor roads ($V_a^{(0)}$) but after traffic calming, there is a 60 km/h limit for minor access roads (V_a).

To calculate travel times on these roads the speed of the vehicles is estimated. This is lower than the limit and lower than the averages of free-flowing vehicles because of drivers accelerating and decelerating when entering or leaving a road, in combination with delays caused by slower vehicles. Systematic data of speeds on minor rural roads are scarce and restricted to mean speeds of free flowing motor vehicles.[1] We assume that the effective speed is 15–20 km/h lower than the legal maximum speed. The value holds for major roads with more homogeneous traffic flows and for minor roads with an access function only because of the lower volume and speed on these traffic-calmed roads. In the road network where each road has a mixed function, traffic flows are heterogeneous, causing larger delays, compared with both arterial highways and minor roads with an access function.

The impact of traffic calming on travel time is calculated by comparing the vehicle km travelled per category of road, indicated with the indices *a* and *f* in Table 1 for access and flow roads divided by their effective speeds, $V_a^{(0)}$ for the initial situation, and V_a or V_f for different levels of traffic calming. For the road network with diffuse flows and without traffic calming, the travel time per grid cell, *T* (vehicle h/day) is:

$$T = \frac{2L\lambda}{V_a^{(0)}} \tag{6}$$

For this initial situation, all road links have a local access function and therefore $V_a^{(0)}$ is 60 km/h. For different levels of traffic calming, we distinguish between traffic flows on roads with an access function and roads with a flow function. Using the road lengths and volumes from Table 1 for level (1) with $S = 2$ of traffic calming involving four cells, the travel time per grid cell, $T^{(1)}$, can be formulated as

$$T^{(1)} = \frac{((4L\gamma\lambda/V_a)(4L(1+(1-\gamma))\lambda/V_f))}{4} \tag{7}$$

The generalized formula for level $S = n$ becomes

$$T^{(n)} = \frac{((2n(n-1)L\gamma\lambda/V_a) + (2nL(1+(1-\gamma)(n-1))\lambda/V_f))}{n^2} \tag{8}$$

We expressed the outcome of this relative to the results for the road network with diffuse flows and no traffic calming as a function of *S* and for three degrees of effectiveness ($\gamma = 0.1$, 0.3 and 0.5) with $V_a^{(0)} = 60$ km/h (Fig. 3). For roads with a flow function, we use the estimated effective value of 65 km/h for V_f, while for access roads V_a is 45 km/h. With these effective speeds, travel time will be even smaller than it is in the original situation when the efficiency of bundling is high enough although this does not significantly depend on the scale of traffic calming. When the bundling on flow roads is weaker ($\gamma = 0.5$), travel times per grid cell increase because of more traffic on access roads moving at a reduced speed, with the increase being somewhat higher for more intensive traffic calming. The maximum difference between level (1) ($S = 2$) and (4) ($S = 5$) varies between 1% ($\gamma = 0.1$) and 6% ($\gamma = 0.5$) extra travel time per grid cell.

To gain insight in the sensitivity of the outcome to different estimates for the effective speed levels; a value of $V_f = 60$ km/h is used instead of 65 km/h to represents situations on flow roads with higher volumes relative their capacities and thus a lower level of service. Using this value, travel time always increases, even for level (1) and efficiency $\gamma = 0.1$. The 5 km/h

[1] De Wilde (1997) measured 17,000 motor vehicles in the Netherlands and found averages of 48, 63 and 70 km/h for roads with a pavement width of 3, 4 and 5 m, with a legal speed limit of 80 km/h. Hway-liem (1991) found an average speed of 72 km/h for 1887 motor vehicles on Dutch rural two-lane roads.

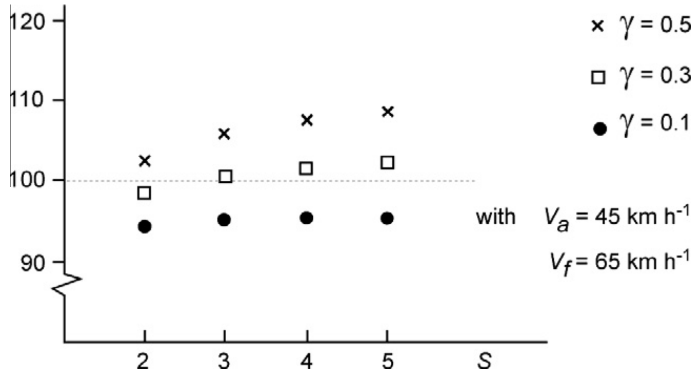

Fig. 3. The relative values for travel time per grid cell for four scales of traffic calming, three levels of effectiveness, for speeds of 65 on flow roads and 45 km h^{-1} on access roads, compared to the initial road network with diffuse flows and without traffic calming. *Source*: Van Langevelde and Jaarsma (2009)

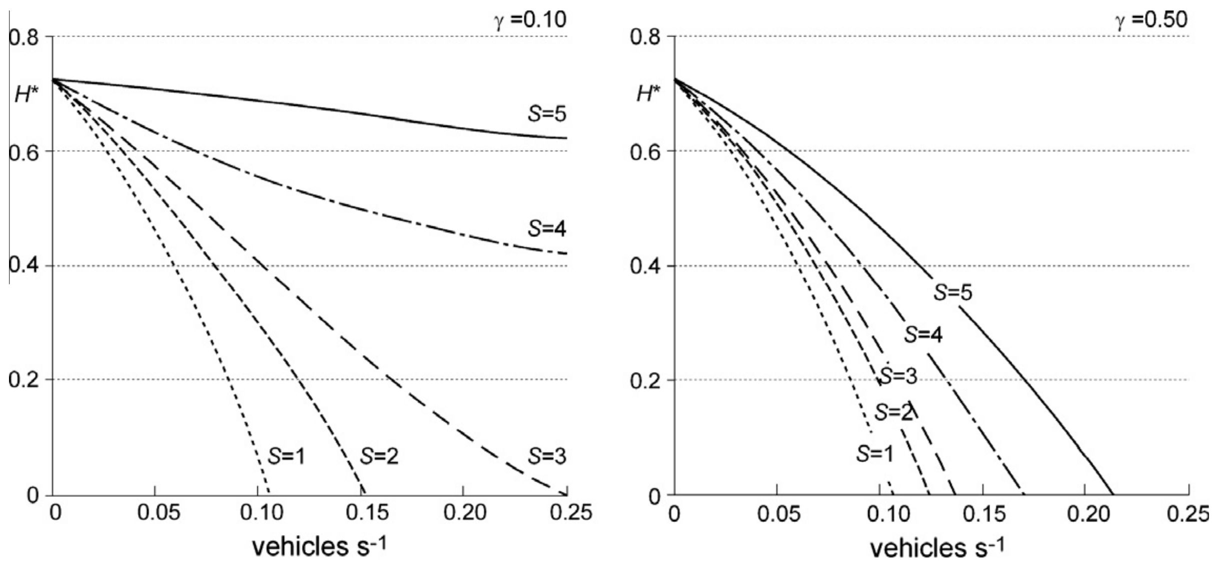

Fig. 4. Fraction of occupied patches H^* of 25 patches as function of the average traffic volume of all roads for different sizes of the traffic-calmed area.

difference in effective speed results in about an 8% increase in travel time, independent of the level of traffic calming. For efficiency $\gamma = 0.5$, this difference is slightly lower.

An alternative approach to estimating the effect of traffic calming is to calculating the extra time from the middle of the traffic-calmed area to the surrounding road network with a flow function. Using speeds on access roads of 60 km/h for the network without traffic calming and 45 km/h after the introduction of calming, traveling a kilometer on an access road will take 20 s extra. For scale level $S = 4$, for example, the maximum distance to a flow road is $2L$ km; while an average situation with $L = 1.1$ km there is less than one minute additional travel time.

3.3. Population persistence for wildlife

To estimate the effect of traffic calming on population persistence for wildlife, a general spatially realistic metapopulation model is used (Hanski and Ovaskainen, 2000, 2002)

$$\frac{dH_i}{dt} = c_i(1 - H_i) - e_i H_i \quad (9)$$

where H_i is the probability of habitat patch i being occupied by a focal species at time t, c_i is the rate at which patch i is colonized by individuals from a surrounding population, and e_i is the rate at which a local population in patch i becomes extinct. The colonization rate c_i and the extinction rate e_i are specified as a function of the connectivity of patch i to the existing local populations and the size of patch i, the latter being used as a surrogate for the local population size.

The probability that individuals colonize habitat patch i not only depends on the distance between the patch and the existing local population, but also factors that reduce the probability that an individual can successfully cover this distance. In areas with relatively high road density, this colonization rate also depends on the number of roads that have to be crossed (Van Langevelde and Jaarsma, 2004). The probability of a successful road crossing depends on the road's traffic volume (λ, expressed in vehicles/s) and by vehicle and species characteristics (Jaarsma et al., 2006). Van Langevelde and Jaarsma (2009) demonstrate the effect of traffic volume on the equilibrium fraction of occupied patches, H^*, for roe deer as the model species and assuming a network of roads in a regular grid with $L = 2$ km in a region of 10 km $\times$ 10 km. The decrease in the fraction of occupied patches H^* with increasing traffic volume of these roads is given in Fig. 4.

Fig. 4 (left panel) holds for an efficient bundling on flow roads ($\gamma = 0.1$) and shows that for roe deer, about 72% of the patches are occupied in a situation without traffic. This fraction decreases with increasing volumes: in a road network without traffic calming with a volume of 0.05 vehicles/s, only 50% of the patches are occupied while the population becomes extinct when traffic volume exceeds 360 vehicles/h. Traffic calming increases these numbers: for level (1), patches will be occupied until a flow of 0.15 vehicles/s, whereas, level (3) flow will allow an occupation rate of 50%. The right panel represents a less effective bundling ($\gamma = 0.5$) and shows that only significant traffic calming improves the occupancy rate (the lines for $S = 2$ and $S = 3$ are close to the initial situation with $S = 1$), if the regional volume, λ, is below 0.15 vehicles/s. These results shows that the efficiency of bundling traffic on flow roads has a much larger impact than more rigorous traffic calming.

4. Conclusions

The analysis indicates that the scale and efficiency of traffic calming significantly affects safety, travel time and population persistence for wildlife. The number of fatalities is reduced by up to 52% when formerly diffuse flows on access roads are bundled on a limited number of flow roads. The gain in safety is somewhat smaller when the traffic-calmed area becomes larger, but this effect is mainly determined by the efficiency of bundling. Metapopulation modeling combined with the probability of successful road crossing for the roe deer as model species illustrates the impact of traffic calming on wildlife moving through the landscape by calculating the fraction of occupied habitat patches. Decisive for the result is the number of access roads with a low volume, and so the efficiency of bundling on flow roads is more important than the scale of traffic calming. The approach, however, should also be applicable to other species that cross roads.

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