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Brief Communication: On direct impact probability of landslides on vehicles

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Abstract

When calculating the risk of railway or road users to be killed by a natural hazard, one has to calculate a "spatio-temporal probability", i.e. the probability for a vehicle to be in the path of the falling mass when the mass falls, or the expected number of affected vehicles in case of an event. To calculate this, different methods are used in the literature, and, most of the time, they consider only the dimensions of the falling mass or the dimensions of the vehicles. Some authors do however consider both dimensions at the same time, and the use of their approach is recommended. Finally, a method considering an impact on the front of the vehicle in addition is discussed.

1 Introduction

Natural hazards impacting on transportation corridors can cause traffic disruption, with direct and indirect economic consequences, and affect the users by direct impact on vehicles (hereafter refereed to as "direct impact") or by impact of the user with deposited material.

When the indirect consequences (e.g. economical cost of the road closure) are taken into account, they generally largely outweigh the direct consequences. However, indirect consequences have no influence on the individual risk, which is often used as an acceptability criterion (e.g. Ho and Ko, 2009). Therefore, the impact of vehicles with falling or deposited material is worth attention. On the other hand, according to Pantelidis (2011), direct impact of a landslide on a moving vehicle is by far less likely than the impact of a vehicle with the landslide material deposited on the road. Nevertheless, using an inappropriate formulation to calculate the direct impact probability might still have a noticeable effect on the total risk assessment.

This paper reviews the approaches used to calculate the direct impact probability knowing an event occurs. This is usually called "spatio-temporal probability" although that, depending on the hypothesis and formulation, it is an expected number of vehicles rather than a formal probability. It has to be mentioned that some methods also consider traffic jam situations, or account for the possibility of a warning system or for the driver to see the event in advance and to respond by braking. These situations are however beyond the scope of this article, where we concentrate on the category named “impact of a falling rock on a moving vehicle” by Bunce et al. (1997), keeping in mind that the calculation applies also to other falling or flowing material such as debris-flow or snow avalanches. For this review, the approaches are divided in three categories, namely: neglecting the event dimension (Sect. 2.1), neglecting the vehicle dimension (Sect. 2.2) and, finally, taking both dimensions into account (Sect. 2.3).

2 Spatio-temporal probability for moving vehicles

2.1 Approaches neglecting the events dimension

Most of the quantitative risk analysis for moving vehicles published in the literature concerns rockfalls. To calculate the probability of a falling block hitting a car or a train, Eq. (1) is generally used (e.g. Bunce et al., 1997; Fell et al., 2005; Ferlisi et al., 2012; Mignelli et al., 2012; Corominas and Mavrouli, 2013; Wang et al., 2014; Macciotta et al., 2015):

$$P_{\mathrm{ST}} = \frac{f_{\mathrm{V}} \times L_{\mathrm{V}}}{v_{\mathrm{V}}} \tag{1}$$

where (correspondence of the variables names used in this paper with those adopted in some of the cited works can be found in Appendix B):

- P_{ST} is the spatio-temporal probability of a vehicle being in the path of the rock falls when it falls, neglecting the rock dimensions and considering a single lane with no vehicle overlap;
- f_{V} is the traffic density expressed in number of vehicles per time unit (e.g. average annual daily traffic (AADT) with proper unit conversion);

- L_V is the length of the vehicle;
- v_V is the mean vehicle velocity.

The aim of this equation is to calculate, as the block falls, the probability that a car is present at the instantaneous position of the block's center of mass. The simplification of using the center of mass of the block is valid only for L_V significantly larger than the size of the falling block, which is usually the case for trains, but might become an oversimplification for cars. In this case, P_{ST} is formally a probability, since a value of one would mean that cars drive bumper to bumper.

The approach proposed by Peila and Guardini (2008) and used by Budetta et al. (2015) falls in the same category, although it takes into account the length of the hazard zone and the vehicle's length. However, if we multiply their spatial probability with their temporal probability and with the vehicle frequency, we obtain:

$$\frac{L_V}{L_H} \times \frac{L_H}{v_V} \times f_V = \frac{L_V \times f_V}{v_V} \tag{2}$$

where L_H is the length of road included in the hazard zone. The simplification is then similar to Eq. (1). It has to be noted that Peila and Guardini (2008) use a binomial distribution to calculate the probability of one or more impacts using the rockfall frequency as number of experiments, and the spatial probability as probability of success. We neglected this transformation here in order to keep the rockfall frequency out of the calculation, but the general idea is the same. This method is modified from Crosta et al. (2001) and corrects the initial mistakes.

2.2 Approaches neglecting the vehicle dimension

Two examples of methods neglecting the vehicle dimension are those applied in Switzerland and the "Average Vehicle Risk" method.

2.2.1 Approach used in Switzerland

Risk analysis in Switzerland has been standardized by the requirement for the regional authorities to establish danger maps (Raetzo et al., 2002), and by the attribution of subsidies for protective measures based on standardized cost-benefit analysis using intensity maps established during the procedure of danger mapping (Bründl et al., 2009). Systematic risk assessment is also being established for highways (Dorren et al., 2009) and for railways (Bründl et al., 2012).

The procedure used to design danger maps consists in establishing scenarios for three different return periods, namely 30, 100 and 300 years. The return period is defined for the source area, and intensity maps are built for each scenario, in order to identify the spatial distribution of the potential intensities. The conditional probability of the source material reaching any downslope location is considered only in a boolean way, which means that the entire endangered area is considered having the same probability to be affected. The three intensity maps are then combined to build the so-called "danger map", keeping the highest danger level obtained by plotting the intensity-frequency combinations in a matrix. This last step is performed for land planning, but when it comes to risk analysis, intensity maps are used. Since the intensity maps are characterised by the return period of the source and the total extension of the endangered area (generally considered as being equiprobable, which simplifies the calculation), the concept of "spatial occurrence probability" is introduced. This parameter aims at calculating the proportion of the area, respectively the length, defined in the intensity map, which is actually affected in case of event (Fig. 1), or, roughly, the probability for a given location to be affected in the scenario.

Risk is then calculated for each scenario – before being summed to obtain the total risk – using the following formula (modified from Bründl et al., 2009):

$$R = f \times P_{\mathrm{S}} \times P^{*}_{\mathrm{ST}} \times N_{\mathrm{P}} \times \lambda \tag{3}$$

where f is the frequency of the scenario, P_{S} is the spatial occurrence probability, which is defined in Eq. (4), P^{*}_{ST} is the spatio-temporal probability, i.e. the number of expected cars in the portion of the road included in the hazard map (of length L_H), and is defined in Eq. (5), N_P is the mean number of persons per vehicle and λ is their vulnerability.

The spatial occurrence probability is then:

$$P_\mathrm{S} = \frac{W_\mathrm{E}}{L_\mathrm{H}} \tag{4}$$

with W_E being the actual width of the event on the road (i.e. the length of the road actually affected by the event) and L_H the length of the road included in the intensity map (i.e. the hazard zone, Fig. 1). The spatio-temporal probability is given by:

$$P^*_\mathrm{ST} = \frac{f_\mathrm{V} \times L_\mathrm{H}}{v_\mathrm{V}}. \tag{5}$$

Multiplying Eqs. (5) and (4), we can rewrite the spatio-temporal probability as follows:

$$P_\mathrm{ST} = P^*_\mathrm{ST} \times P_\mathrm{S} = \frac{f_\mathrm{V} \times W_\mathrm{E}}{v_\mathrm{V}}. \tag{6}$$

Which means that it calculates the "probability" that the center of mass of a moving vehicle is located in the section covered by the event (W_E). It is then valid only for W_E largely superior to L_V. Since rockfalls are often a problem along roads or railways, this assumption is regularly not met. Few articles uses this formulation (e.g. Dorren et al., 2009; Voumard et al., 2013, as a comparison with the risk that they calculate using a traffic simulator), but it is commonly used in practice. Zischg et al. (2005) use this formulation for snow avalanches impacting cars, which is then an acceptable simplification since W_E is generally large. In this case, P_ST is formally not a probability, since several cars can be in the affected section simultaneously. It is indeed the expected number of affected cars.

2.2.2 The "Average Vehicle Risk" method

A similar approach, neglecting the dimension of the vehicle, is the Average Vehicle Risk (AVR) method used in the Rockfall Hazard Rating System (RHRS) (Pierson and

Van Vickle, 1993; Budetta, 2002, 2004; Pierson, 2012). Although the RHRS is not intended at quantitatively assessing the risk, the AVR criterion correspond to a spatio-temporal probability and is calculated as follows:

$$P_{\mathrm{ST}} = \frac{f_{\mathrm{V}} \times L_{\mathrm{H}}}{v_{\mathrm{V}}} \quad (7)$$

where P_{ST} corresponds to the variable AVR of the original methodology, except that it is not expressed here in percent. This method uses L_{H}, which is the length on the hazard section ("slope length" in the original methodology), and neglects both the the vehicle dimension (L_{V}) and the event dimension (W_{E}). In this formulation, P_{ST} often takes a value above 1, meaning that on average, more than one car is expected in the studied section.

Although this method is mostly used as an index rather than as a quantity, its use might lead to inexact results. Indeed, in Pierson and Van Vickle (1993) and Budetta (2004), the rating includes a frequency, which, for similar susceptibilities, is dependent of the considered slope length. At the same time, P_{ST} also reflects the slope length, which means that this parameter is considered twice in the classification. On the other hand, Ferlisi et al. (2012) modified the RHRS by using a frequency normalised to a unit slope length, which means that the section length is reflected only in P_{ST}, being then coherent.

2.3 Approaches using both dimensions

2.3.1 Methods considering an impact on the side of the vehicle

Few articles uses both event size and vehicle length for a more complete risk assessment. Hantz (2011) uses a risk calculation where the block size varies according to a power law, and the target dimension is set at 50 cm, corresponding to a hicker's length. Michoud et al. (2012) also use the dimensions of the cars (4 m) and of the falling rocks. Borter (1999), in the original Swiss risk methodology, takes into account both the dimension of the falling mass and the length of the vehicle when estimating the risk for a train. This approach has been integrated recently in the official risk calculator “EconoMe” for trains traffic (Bründl et al., 2015), but the approach presented in Sect. 2.2.1 is still used for road traffic. This approach has also been presented by Hazzard (1998, p. 185). In these studies, the spatio-temporal probability is calculated as follows:

$$P_{\mathrm{ST}} = \frac{f_{\mathrm{V}} \times (W_{\mathrm{E}} + L_{\mathrm{V}})}{v_{\mathrm{V}}}. \tag{8}$$

The reason for the addition of W_{E} and L_{V} is illustrated in Fig. 2. P_{ST} is then independent from the length of the hazard area L_{H}. It has to be mentioned that this equation will give inexact results in the case of a multiple path event, as the one presented in Fig. 1. Indeed, to be exact, the vehicle length should be added to the width of every path, which is not the case if the total width of the event is used. Cloutier (2014) also uses the two dimensions, but the equation differs by considering, in addition, the braking time and the time since the last inspection (to account for the impact with deposited material), which is beyond the scope of this review.

In addition, Borter (1999) proposes to calculate the number of affected people on a train using the length of the event and the total number of passengers on the train ($N_{\mathrm{P}}^{\mathrm{total}}$):

$$N_{\mathrm{P}}^{\mathrm{affected}} = \frac{N_{\mathrm{P}}^{\mathrm{total}} \times W_{\mathrm{E}}}{L_{\mathrm{V}}}. \tag{9}$$

$N_{\mathrm{P}}^{\mathrm{affected}}$ replaces then N_{P} in the risk calculation (Eq. 3), the risk being otherwise overestimated for long trains. The passengers “length” could also be added to the event’s width in this equation, similarly to the addition of the event’s width to the vehicle’s length in P_{ST} (Eq. 8) or to the hicker’s length in Hantz (2011), to account for the fact that a passenger with a center of mass close to the path of the falling mass could actually be partly on its path. This is however a detail with respect to the fact that this last equation does not take into account the potential derailment of the train (see Cloutier, 2014), which could affect the passengers on a section of the train longer than the one directly affected by the falling material.

2.3.2 Methods considering an impact on the side and front of the vehicle

The most complete method is probably the one proposed by Roberds (2005), who uses a complex conditional probability model. The part of the model concerning the direct impact probability consists in calculating the probability that a falling mass passes between uniformly spaced vehicles, and to take its complement to one. The calculation is made as follows:

$$P_{\mathrm{ST}} = 1 - \frac{\left[L_{\mathrm{S}} - (L_{\mathrm{E}} + W_{\mathrm{V}})\frac{v_{\mathrm{V}}}{v_{\mathrm{E}}}\right] - W_{\mathrm{E}}}{L_{\mathrm{S}} + L_{\mathrm{V}}} \tag{10}$$

where the vehicle V is characterised by a length L_{V}, a width W_{V} and a velocity v_{V}, while the falling mass is characterised by a length L_{E} (perpendicular to the vehicle length), a width W_{E} and a velocity v_{E}. L_{S} is the spacing between the vehicles and depends on the traffic density (Fig. 3). With this approach, the possibility for a car to collide frontally with an event occurring is taken into account (see Appendix A). The limit of this method consists in considering that vehicles are uniformly spaced, but the impact probability is actually higher if they are not. Indeed, since L_{S} is present in the numerator and in the denominator, and since the numerator is always smaller than the denominator, a negative change in L_{S} (denoted ΔL_{S}) will result in a positive change in P_{ST} (denoted ΔP_{ST}) larger, in absolute values, than the ΔP_{ST} resulting from an equivalent positive ΔL_{S}. Therefore, on average, P_{ST} with L_{S} varying around a mean $\bar{L}_{\mathrm{S}}$ will be larger than P_{ST} resulting from a constant $L_{\mathrm{S}} = \bar{L}_{\mathrm{S}}$.

3 Synthetic examples

Two examples of risk calculation using the different methods are given in Tables 1 and 2, respectively for cars and for trains. The risk is calculated only for direct impacts. In case of rock falls affecting cars, the spatio-temporal probability using Eq. (1), which is widely used in the literature, is aound 18 % lower than if both dimensions are used (Eq. 8) and 43 % lower than considering an impact on the side and front (Eq. 10). Neglecting the size of the vehicle (Eq. 6) gives a P_{ST} farther from the expected value (obtained with Eq. 10). For cars, the difference in P_{ST} is directly reflected on the risk estimation.

When it comes to trains, the spatio-temporal probability is largely inferior with Eq. (6). However, if $N_{\mathrm{P}}^{\mathrm{affected}}$ is used when needed, the risk estimations are quite similar with the different methods. We consider that $N_{\mathrm{P}}^{\mathrm{affected}}$ is needed whenever L_{V} is taken into account. Indeed, if L_{V} is not used (Eq. 6), P_{ST} consider the vehicle as being dimensionless. Therefore, P_{ST} in Eq. (6) is somehow already the probability for a train user to be affected.

4 Discussion and conclusions

Although risk resulting from direct impact of the event with a moving vehicle is generally lower than the risk of a moving vehicle hitting debris deposited on its way, neglecting the dimension of the event or the dimension of the vehicle might lead to an inexact result if the neglected dimension is not significantly lower than the one taken into account. Therefore, we recommend to always prefer Eq. (8) to Eqs. (1) and (6), in order to avoid significant errors. Although, as shown in Table 2, the difference in risk evaluation for the passengers might be reduced to a reasonable level by using a suitable method to calculate the number of affected people, an incorrect P_{ST} could also affect other consequences scenarios, such as train derailment. Indeed, if P_{ST} is used to calculate the probability of a road or railway closure after a vehicle has been hit by a falling mass (disregarding if a passenger has been affected or not), then the method used to calculate P_{ST} really matters (considering that the closure will be longer if a train has to be removed from the track than if the track only needs to be cleared from fallen materials). In addition, the calculation of $N_{\mathrm{P}}^{\mathrm{affected}}$ (Eq. 9) highlights the fact that the rest of the risk calculation has to be coherent with the calculation of P_{ST}. Indeed, if P_{ST} is the probability that a vehicle is hit by a falling mass, then whether (1) the vulnerability is the conditional probability for a passenger to die if any part of the vehicle is affected, or (2) the number of people should be reduced with Eq. (9) if the vulnerability is the conditional probability for a passenger to die if the part of the vehicle where he or she is located is affected.

More in depth analysis could also be performed using the approach presented in Eq. (10), which is the only formulation presented here that takes into account the possibility of a frontal impact with a moving vehicle. However, this approach needs many parameters that are not always easy to assess, and the results are different if the spacing between the cars is not constant. Moreover, this latter method considers the impact of a vehicle with a falling mass crossing the road, but, in many situations, the falling mass will stop on the road or on the railway and cause much higher risk. Indeed, it is for example especially crucial for trains to take into account the probability of impacting material deposited on the path because trains have limited chances of avoiding contact if rock falls debris are on the rail track and if the train operators are not informed of the situation ahead, that is because trains have large stopping distances (particularly freight train) and cannot manoeuvre to avoid debris.

To conclude, it is important to understand that the present communication only aims at discussing the spatial interaction of two moving objects, namely the falling mass and the vehicle, and that other consequences scenarios such as the impact with deposited material or the economic consequences of a road or railway closure should be analysed in addition if applicable.

Appendix A: Demonstration of Roberds (2005) approach

Considering a mass of debris of length L_{E} and width W_{E} falling on a road with a velocity v_{E} (Fig. 3). On the road, vehicles of length L_{V} and width W_{V} are moving with a velocity v_{V}, and are separated from each other with a constant distance L_{S}. The time needed by the falling mass to completely cross the vehicle's trajectory is:

$$t = \frac{W_{\mathrm{V}} + L_{\mathrm{E}}}{v_{\mathrm{E}}}. \tag{A1}$$

During this time, the vehicles will move forward of the distance:

$$d = v_{\mathrm{V}} \times t = v_{\mathrm{V}} \times \frac{(W_{\mathrm{V}} + L_{\mathrm{E}})}{v_{\mathrm{E}}} = (W_{\mathrm{V}} + L_{\mathrm{E}}) \times \frac{v_{\mathrm{V}}}{v_{\mathrm{E}}}. \tag{A2}$$

If we consider that the vehicles in Fig. 3 are static, the leftmost abscissa where the moving mass can cross the road equals:

$$x_0 = \frac{1}{2} W_{\mathrm{E}}. \tag{A3}$$

This coordinate equals half of the debris width, since the reference system of the debris is located at its center.

With static vehicles, the rightmost abscissa x_1 would be L_{S} minus half of the width of the falling mass, similarly to x_0. However, since the vehicles are moving, the distance travelled by the car during the time spent by the falling mass crossing the road (d) needs to be removed from x_1.

$$\begin{aligned} x_1 &= L_{\mathrm{S}} - d - \frac{1}{2} W_{\mathrm{E}} && \text{(A4)} \\ &= L_{\mathrm{S}} - \left((W_{\mathrm{V}} + L_{\mathrm{E}}) \times \frac{v_{\mathrm{V}}}{v_{\mathrm{E}}} \right) - \frac{1}{2} W_{\mathrm{E}} && \text{(A5)} \end{aligned}$$

Therefore, the distance on the abscissa which is available for the block to cross without affecting a car is:

$$\begin{aligned}
\Delta x &= x_1 - x_0 && \text{(A6)}\\
&= L_\mathrm{S} - \left((W_\mathrm{V} + L_\mathrm{E}) \times \frac{v_\mathrm{V}}{v_\mathrm{E}}\right) - \frac{1}{2}W_\mathrm{E} - \frac{1}{2}W_\mathrm{E} && \text{(A7)}\\
&= L_\mathrm{S} - \left((W_\mathrm{V} + L_\mathrm{E}) \times \frac{v_\mathrm{V}}{v_\mathrm{E}}\right) - W_\mathrm{E}. && \text{(A8)}
\end{aligned}$$

The probability for the block to cross the road without affecting a car $P_{\overline{\mathrm{ST}}}$ is the proportion of favourable abscissa Δx compared to the total distance $L_\mathrm{S} + L_\mathrm{V}$. Therefore, the probability for the block to affect a car P_ST is the complementary of $P_{\overline{\mathrm{ST}}}$:

$$\begin{aligned}
P_\mathrm{ST} &= 1 - P_{\overline{\mathrm{ST}}} && \text{(A9)}\\
&= 1 - \frac{\left[L_\mathrm{S} - (L_\mathrm{E} + W_\mathrm{V})\,\frac{v_\mathrm{V}}{v_\mathrm{E}}\right] - W_\mathrm{E}}{L_\mathrm{S} + L_\mathrm{V}}. && \text{(A10)}
\end{aligned}$$

Appendix B: Variable names

A table of correspondence of the variable names in the literature is given in Table A1.

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Table 1. Example of risk calculation for car passengers (direct impact only). Parameters are shown only when used in the calculation.

Parameter	Dimension	Eq. (1)	Eq. (6)	Eq. (8)	Eq. (10)
f_V	[vehicles day^{-1}]	5000	5000	5000	5000
L_V	[m]	4.5	–	4.5	4.5
W_V	[m]	–	–	–	2
v_V	[km h^{-1}]	80	80	80	80
W_E	[m]	–	1	1	1
L_E	[m]	–	–	–	1
v_E	[km h^{-1}]	–	–	–	100
L_S	[m]	–	–	–	379.5
P_{ST}	[–]	1.17×10^{-2}	2.60×10^{-3}	1.43×10^{-2}	2.06×10^{-2}
H	[yr^{-1}]	0.1	0.1	0.1	0.1
V	[–]	0.5	0.5	0.5	0.5
N_P	[persons]	1.76	1.76	1.76	1.76
R	[persons yr^{-1}]	1.03×10^{-3}	2.29×10^{-4}	1.26×10^{-3}	1.81×10^{-3}

Table 2. Example of risk calculation for train passengers (direct impact only). Parameters are shown only when used in the calculation.

Parameter	Dimension	Eq. (1)	Eq. (6)	Eq. (8)	Eq. (10)
f_V	[vehicles day^{-1}]	30	30	30	30
L_V	[m]	200	–	200	200
W_V	[m]	–	–	–	2
v_V	[km h^{-1}]	150	150	150	150
W_E	[m]	–	1	1	1
L_E	[m]	–	–	–	1
v_E	[km h^{-1}]	–	–	–	100
L_S	[m]	–	–	–	1.20×10^5
P_{ST}	[–]	1.67×10^{-3}	8.33×10^{-6}	1.68×10^{-3}	1.71×10^{-3}
H	[yr^{-1}]	0.1	0.1	0.1	0.1
V	[–]	0.5	0.5	0.5	0.5
N_P^{total}	[persons]	175	175	175	175
$N_P^{affected}$	[persons]	0.9	–	0.9	0.9
R	[persons yr^{-1}]	7.29×10^{-5}	7.29×10^{-5}	7.33×10^{-5}	7.49×10^{-5}

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table A1. Correspondence of selected variables names used in this paper with the original methodologies.

Name in this paper	P_{ST}	f_{V}[a]	L_{V}	v_{V}	W_{E}	P_{S}	P^*_{ST}	L_{H}
Bunce et al. (1997)	$P(S:H)$	N_{v}	L_{V}	V_{V}	–	–	–	–
Dorren et al. (2009)	Nc	AHT	–	Vmax	slide width	Pso	–	–
Bründl et al. (2009)	–	MDT	–	v	–	$p(s)$	$p(\mathrm{et})$	g
Pierson (1991)	AVR	ADT	–	Posted speed limit	–	–	–	Slope length
Borter (1999, p. 76)	p_{Pr}	F_{Z}	L_{Z}	v	g	p_{rA}	–	–
Roberds (2005)	$P4_1$	λV	V_{L}	V_{v}	D_{W}	–	–	–
Peila and Guardini (2008)	$P(A)_{\mathrm{tot}}$[b]	$N_{\mathrm{v/a}}$	L_{v}	V_{v}	–	–	–	L_{p}

[a] The correction factors applied to f_{V} are not considered here.

[b] The original variable considers the number of falling blocs in addition.

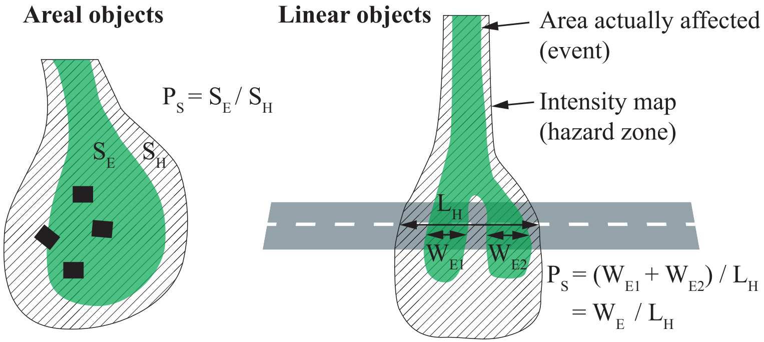

Figure 1. Calculation of the spatial occurrence probability (P_S) as used in the Swiss methodology. This probability corresponds to the proportion defined in the hazard map which is actually affected in case of event (left panel), or to the proportion of the length which is affected (modified from Bründl et al., 2015).

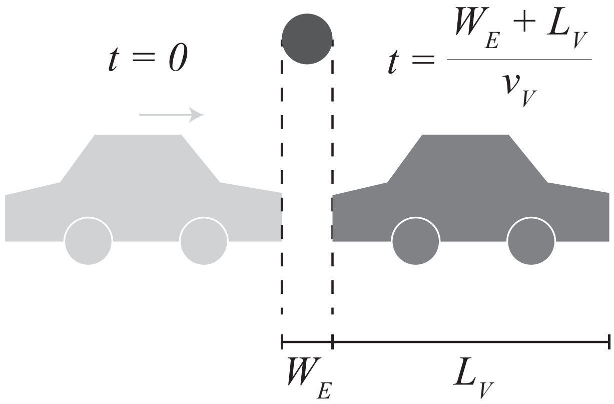

Figure 2. Spatio-temporal probability considering both vehicle and event size. Every vehicle located between the left and the right position will be affected by the rockfall, which means that the spatio-temporal probability will depend on the time needed to travel the distance $W_\mathrm{E} + L_\mathrm{V}$, as denoted in Eq. (8). Another way to see this is that a block will affect a car if its center falls closer to $(1/2)W_\mathrm{E}$ in front or behind the car.

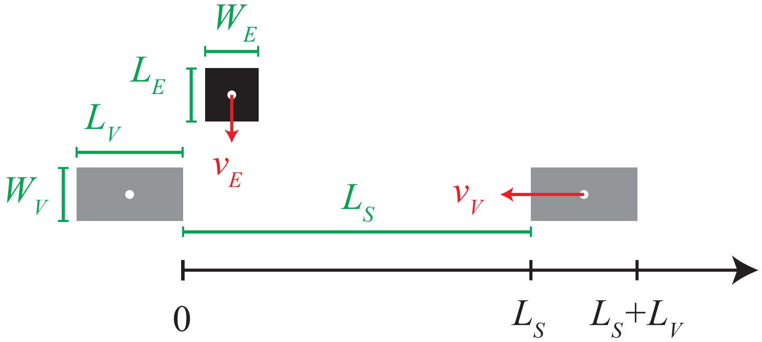

Figure 3. Parameters of the cars (in grey) and the falling mass (in black) used for the calculations in Roberds's (2005) method. The origin of the abscissa axis is located at the rear of the front car.