

Article

Cross-Passage Blockage Probability in Railway Tunnels: A Geometric-Probabilistic Contribution to Collective Risk Assessment

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Abstract

This study examines whether a train fire near an evacuation interface in a railway tunnel can create an adverse configuration relevant to evacuation design and collective risk assessment. It focuses on twin single-track tunnels, in which the parallel tunnel serves as a safe area, and evacuation is carried out through cross-passages and boundary portals. If a fire impairs such an interface, evacuees may be forced to continue to a more distant exit. The problem is formulated as a geometric-probabilistic screening task. The model calculates the probability that, after the train has stopped, the fire lies within a tolerance zone around an evacuation interface. The probability is derived analytically using deterministic convolution and verified via Monte Carlo simulation for trains with lengths of 200 m and 400 m. This verification concerns mathematical calculation only, not the physical, smoke, operational, or evacuation assumptions. The geometric probability is linked to collective risk through representative train fire frequencies, external consequence indicators, and selected F/N criteria. With $\varepsilon = 37$ m and portals included as boundary evacuation interfaces of the finite tunnel domain, the adverse-configuration probabilities are similar: approximately 14.0% for the 200 m train and 14.6% for the 400 m train. The difference becomes decisive only after considering the magnitude of the consequences and the traffic intensity. Under the reference assumptions, the 400 m high-occupancy case reaches the selected Dutch criterion at about four train passages per day. A fire near an evacuation interface, therefore, cannot be treated as marginal solely because the tunnel meets the 500 m cross-passage spacing requirement. Acceptability depends on geometry, occupancy, fire frequency, the definition of consequences, traffic intensity, and the selected risk framework. The homogeneous fire-origin distribution is used only as a neutral first-order assumption; more refined spatial fire-origin models and broader comparisons across safety criteria are needed.



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1. Introduction

A fire involving a railway vehicle inside a tunnel can quickly create smoke conditions that hamper evacuation. Early in a tunnel fire, the lower part of the tunnel cross-section may remain tenable, but descending smoke can progressively reduce this tenable layer [1]. Rescue and evacuation are complicated by confined space, limited access, ventilation conditions, and communication constraints. Studies show that tunnel fire safety depends

on fire development, smoke control, evacuation, and safety systems [2]. The rare, high-impact nature of these fires requires safety planning that considers both the probability of the event and its potential consequences. Incidents such as the Hokuriku (1972) and Channel Tunnel (1996) fires led to stricter requirements for detection, smoke control, and evacuation routes [3]. In the Czech Republic, the development of high-speed rail increases the importance of fire safety [4]. For twin-bore single-track tunnels, the parallel tunnel often serves as a safe area, with evacuation through cross-passages. The SRT TSI requires cross-passages at intervals of no more than 500 m when the adjacent tunnel tube is used as a safe area [5]. This prescribed minimum spacing does not by itself demonstrate that all adverse fire configurations are negligible. Recent simulation studies suggest that spacing and safety features should be evaluated against fire and evacuation scenarios [6,7].

Although the SRT TSI sets a minimum, countries often apply stricter risk-based approaches. Sweden links tunnel safety to explicit goals and uses F/N diagrams and ALARP [8,9]. The Netherlands requires risk and scenario analyses, with a “groepsrisico” standard of $0.03/N^2$ per km per year [10]. Cross-passage spacing can therefore be complemented by collective-risk criteria, particularly when a single event may affect many occupants [10,11]. Recent fire risk studies show that estimates vary depending on the assessment method, tenability criteria, and the coupling between fire and evacuation [7]. For Czech high-speed tunnels, this study examines a train fire near an evacuation interface following a stop. Evacuation interfaces include internal cross-passages and portals. If such an interface is compromised by heat or smoke, evacuees may be forced to move to a more distant exit. Geometrically, this can increase the walking distance from one cross-passage spacing, s , to approximately two spacings, $2s$; for $s = 500$ m, the distance may approach 1000 m. Recent CFD and evacuation studies confirm the importance of spatial interactions between smoke, evacuation movement, tenability conditions, and escape routes [11–13].

The question is not whether this scenario alone defines tunnel safety but whether it is frequent enough to be included in collective-risk screening. Collective risk links event frequency with the number of affected persons and is commonly represented by F/N curves [11,12]. The present study, therefore, isolates the geometric probability of a fire occurring within a tolerance zone around an evacuation interface and then couples this probability with representative train fire frequencies, externally derived consequence indicators, and selected F/N criteria. The event probability is calculated analytically using deterministic convolution and verified numerically by Monte Carlo simulation. Monte Carlo verification is used only to check the mathematical implementation of the geometric calculation; it does not validate the physical fire, smoke, operational, or evacuation assumptions.

2. Methods

2.1. Model and Hypothesis Formulation

A fire on a railway vehicle in a tunnel is rare but potentially severe; its risk is therefore assessed through both event frequency and consequence magnitude. Probabilistic and deterministic methods are commonly used in tunnel risk assessment, with societal risk often represented by F/N curves [8,9,12]. Fire-frequency values used in this study are summarized in Table 1. The representative input value used in this study is the European median calculated from the values of the EU, the Netherlands, Germany, France, Austria, and Italy. The resulting EU median is $0.01455 \times 10^{-6} \text{ tr}^{-1} \cdot \text{km}^{-1}$. This European selection is consistent with the EU interoperability and SRT TSI context of the present assessment. The source studies use railway-vehicle fire frequencies in the context of a passenger railway tunnel QRA [14–16]. Recent tunnel fire and railway tunnel studies also show that risk estimates depend on fire development, smoke spread, evacuation modeling, tenability criteria, and safety system performance [2,7,13]. The study evaluates the adverse configuration in

which a train fire occurs near an evacuation interface after the train has stopped inside the tunnel. The study tests whether the annual frequency of this adverse configuration remains below the selected F/N criterion. The geometric probability π is therefore not compared directly with a probability threshold; it is first combined with train fire frequency and annual traffic intensity to obtain the scenario frequency $F_{sc}(n)$.

$$H_0 : F_{sc}(n) \leq F_{lim}(N) \quad (1)$$

$$H_1 : F_{sc}(n) > F_{lim}(N) \quad (2)$$

The model represents a severe subset of railway-vehicle fire scenarios involving a stop in the tunnel. It does not describe normal operational behavior. If the train remains controllable, the driver would normally attempt to reach a portal, station, cross-passage area, or another safer stopping location [5,17,18]. Such behavior needs a conditional stopping model considering detection time, braking distance, traction, rules, and evacuation distance [5,17,18]. It addresses a different operational question and was not included in the geometric screening calculation. The stopping position and fire-origin position are treated as uniformly distributed first-order assumptions. The uniform fire-origin distribution is not interpreted as conservative. Modern high-speed trains may have non-uniform ignition-risk zones associated with traction equipment, converters, transformers, batteries, HVAC units, auxiliary systems, luggage areas, or passenger compartments [2,7]. A subsystem-specific distribution would be preferable if sufficiently robust fleet-specific data were available [2,7]. This limitation is relevant because the cases reflect future high-speed passenger trains around 2030, not a specific fleet with known fire statistics.

The geometric model is defined by the tunnel length T , the evacuation interface spacing s , the train length L , and the tolerance distance ε . Evacuation interfaces include internal cross-passages and boundary portals. The entrance and exit portals were included as boundary evacuation interfaces because they may serve as evacuation exits from the tunnel. However, their interpretation of consequences differs from that of internal cross-passages. Blockage of an internal cross-passage may affect evacuation from both adjacent tunnel sections and can increase the walking distance to the next available cross-passage. In contrast, a portal marks the boundary of the tunnel system; if a fire occurs near a portal, the relevant evacuation geometry is asymmetric because one direction leads to the outside of the tunnel. Internal cross-passages are located at $c_k = k \cdot s$, $k = 1, 2, \dots, 9$, i.e., at 500, 1000, ..., 4500 m. The entrance and exit portals at 0 m and 5000 m are included as boundary evacuation interfaces. In the reference configuration, $T = 5000$ m, $s = 500$ m, and two train lengths are analyzed: $L_{200} = 200$ m and $L_{400} = 400$ m, as shown in Figure 1. Normative spacing requirements are based on the SRT TSI and are compared with risk-based approaches using explicit societal-risk criteria [4,8,9,17]. The tolerance distance ε represents the longitudinal distance from an evacuation interface within which thermal conditions may impair or prevent its safe use. In the reference case, $\varepsilon = 37$ m. This value is scenario dependent and should not be interpreted as the flame length or the point-source radiation distance [19]. In a tunnel, exposure near an evacuation interface may result from direct flame radiation, radiation from the hot smoke layer, convective heating by hot gases and the ceiling jet, and re-radiation from heated tunnel surfaces [2,20–22]. The $2.5 \text{ kW} \cdot \text{m}^{-2}$ heat-flux criterion is used as the tenability reference [20]. Because ε directly controls the width of the critical zone, the Results include a sensitivity analysis for $\varepsilon = 25$ m, 37 m, and 50 m.

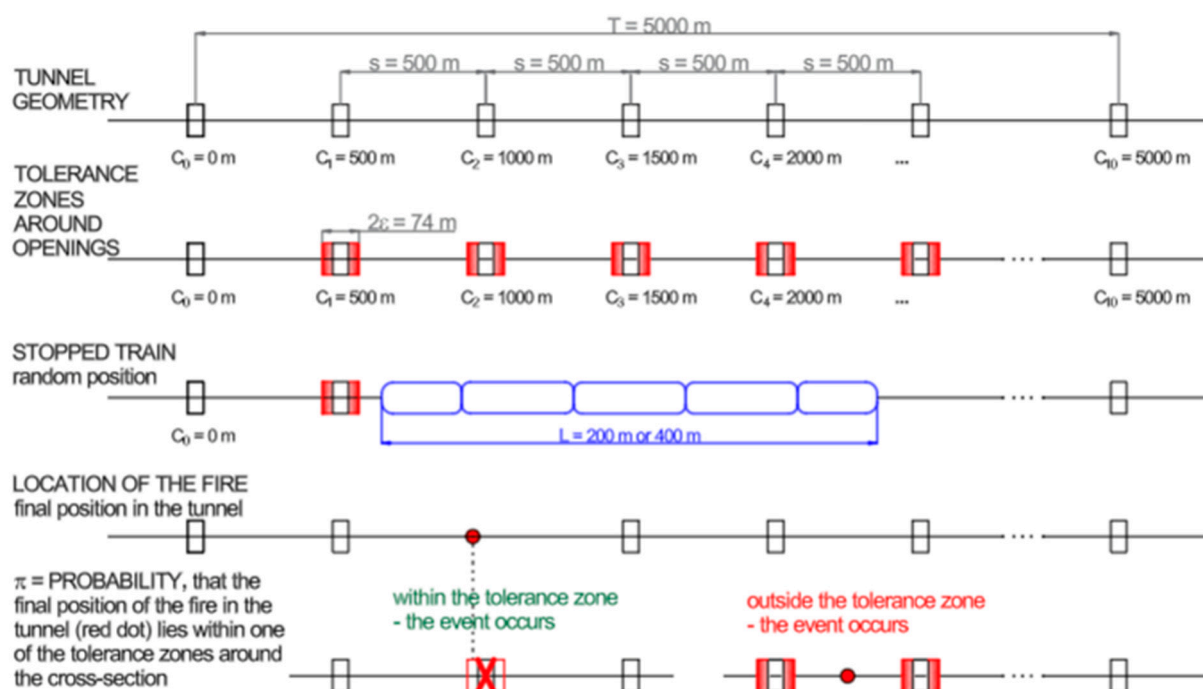


Figure 1. Schematic of the geometric-probabilistic model. A train of length $L = 200 \text{ m}$ or 400 m stops at a random admissible position in a 5000 m tunnel with cross-passages spaced at $s = 500 \text{ m}$. The fire origin is uniformly distributed along the train. The event occurs when the final fire position lies within a tolerance zone of width $2\varepsilon = 74 \text{ m}$ around a cross-passage.

Table 1. Railway-vehicle fire frequencies reported by [15,16], including the original data sources cited in those studies. Values are given in 10^{-6} fires per train-kilometer ($\text{tr}^{-1} \cdot \text{km}^{-1}$). The European median is therefore used here as a passenger-relevant screening input within the EU interoperability and SRT TSI framework.

State/Region	Fire Frequency in [15]. [$10^{-6} \text{ tr}^{-1} \cdot \text{km}^{-1}$]	Source	Fire Frequency in [16]. [$10^{-6} \text{ tr}^{-1} \cdot \text{km}^{-1}$]	Source
Korea—passenger transport/passenger vehicles	0.0130	Domestic statistics after 2001, as described in [15], are the average fire frequency for passenger trains	0.0130	Korea Railroad and Korea Rail Network Authority. Statistical Yearbook of Railroad 2015
Japan	0.0013	Ministry of Land, Infrastructure and Transport, Railway Bureau, Japan. Railway Statistical Yearbook, Heisei 18	0.0013	G & B Engineering Corporation. Korea Rail Network Authority, Prepared for QRA Criteria for Vehicle Fire Intensity and QRA of Daegok–Sosa Double Track Railway
USA	0.0299	Transportation Safety Board rail statistics webpage	0.0299	G & B Engineering Corporation. Korea Rail Network Authority, Prepared for QRA Criteria for Vehicle Fire Intensity and QRA of Daegok–Sosa Double Track Railway
EU	0.0358	Eurostat	—	—
The Netherlands	0.0100	Molag, M., van Mierlo, R., and Wiersma, T. Realistic Fire Scenarios for Safety Assessment of Train Fires in Tunnels	—	—
England	—	—	0.0572	G & B Engineering Corporation. Korea Rail Network Authority, Prepared for QRA Criteria for Vehicle Fire Intensity and QRA of Daegok–Sosa Double Track Railway
Germany	—	—	0.0143	G & B Engineering Corporation. Korea Rail Network Authority, Prepared for QRA Criteria for Vehicle Fire Intensity and QRA of Daegok–Sosa Double Track Railway

Table 1. Cont.

State/Region	Fire Frequency in [15]. [10 ^{−6} tr ^{−1} ·km ^{−1}]	Source	Fire Frequency in [16]. [10 ^{−6} tr ^{−1} ·km ^{−1}]	Source
France	—	—	0.0274	G & B Engineering Corporation. Korea Rail Network Authority, Prepared for QRA Criteria for Vehicle Fire Intensity and QRA of Daegok–Sosa Double Track Railway
Austria	—	—	0.0017	G & B Engineering Corporation. Korea Rail Network Authority, Prepared for QRA Criteria for Vehicle Fire Intensity and QRA of Daegok–Sosa Double Track Railway
Italy	—	—	0.0148	G & B Engineering Corporation. Korea Rail Network Authority, Prepared for QRA Criteria for Vehicle Fire Intensity and QRA of Daegok–Sosa Double Track Railway
Maximum	0.0358		0.0572	
Median in EU	0.013		0.0146	

2.2. Model Definition Using Deterministic Convolution

Both input variables were modeled as uniform and independent first-order assumptions. The rear-end position of the stopped train, X , was distributed over all admissible stopping positions in the tunnel, and the fire origin, U , was distributed over the train length, as defined in Equations (3) and (4). This assumption keeps the geometric model simple and reproducible and avoids unsupported assumptions about preferred stopping positions or fire-origin locations. The fire position in the tunnel is then obtained as the sum of these two variables, Equation (5). The adverse configuration occurs when the fire position lies within the tolerance distance ε from the nearest cross-passage, as defined in Equation (6). The corresponding probability is denoted by π , Equation (7).

$$X \sim \text{Unif}(0, T - L) \quad (3)$$

$$U \sim \text{Unif}(0, L) \quad (4)$$

$$Y = X + U \quad (5)$$

$$D = \min_k |Y - c_k| \rightarrow A_\varepsilon = \left\{ \min_k |Y - c_k| \leq \varepsilon \right\} \quad (6)$$

$$\pi = \mathbb{P}(A_\varepsilon) \quad (7)$$

The probability π was evaluated analytically by deterministic convolution. The density of the fire position, Y , is obtained from the densities of X and U , Equations (8)–(10), and integrated over the tolerance zones around the cross-passages, Equation (11). The finite-domain formulation retains the tunnel length, train length, cross-passage positions, and boundary effects. A periodic formulation using the phase variable Z , Equation (12), was used only as a comparison for the interior pattern away from tunnel boundaries. Similar deterministic and probabilistic combinations are used in tunnel QRA to link scenario geometry, event frequency, and consequence assessment [12,20].

$$f_X(x) = \frac{1}{T - L} 1_{[0, T - L]}(x) \quad (8)$$

$$f_U(u) = \frac{1}{L} 1_{[0, L]}(u) \quad (9)$$

$$f_Y(y) = (f_X \cdot f_U)(y) = \int_{-\infty}^{\infty} f_X(t) f_U(y-t) dt \quad (10)$$

$$\pi = \int_{(\cup_k [c_k - \varepsilon, c_k + \varepsilon]) \cap [0, T]} f_Y(y) dy \quad (11)$$

$$Z = Y \bmod s \quad (12)$$

2.3. Monte Carlo

Monte Carlo simulation was used to verify the analytical calculation of π . In each run, the train stopping position and the fire-origin position were sampled from the distributions defined in Equations (3) and (4). The resulting fire position and event indicator were then calculated using Equations (13) and (14). The simulation used a defined number of independent runs. For the 200 m train, $X \sim Unif(0, 4800 \text{ m})$ and $U \sim Unif(0, 200 \text{ m})$. For the 400 m train, $X \sim Unif(0, 4600 \text{ m})$ and $U \sim Unif(0, 400 \text{ m})$. The Monte Carlo estimate of the adverse-configuration probability is given by Equation (15). Convergence was checked using the sequential estimate in Equation (16), and the sampling uncertainty was described by the standard error and upper confidence bound in Equations (17) and (18). The distance to the nearest cross-passage, Equation (19), was used only to describe the spatial distribution of fire positions. In this study, a Monte Carlo simulation verifies the numerical implementation of the geometric probability model; it does not validate the physical assumptions of fire, smoke, evacuation, or operations. Similar simulation-based approaches are commonly used in tunnel QRA to estimate stability and to interpret support scenarios [3,8].

$$Y_i = X_i + U_i \quad (13)$$

$$I_i = 1 \left(\min_k |Y_i - c_k| \leq \varepsilon \right) \quad (14)$$

$$\hat{\pi} = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} I_i \quad (15)$$

$$\hat{\pi}_n = \left(\frac{1}{n} \right) \sum_{i=1}^n I_i, n = 1, \dots, N_{MC} \quad (16)$$

$$SE(\hat{\pi}) = \sqrt{\frac{\hat{\pi}(1 - \hat{\pi})}{N_{MC}}} \quad (17)$$

$$\pi_{1-\alpha}^U = \hat{\pi} + z_{1-\alpha} SE(\hat{\pi}) \quad (18)$$

$$D = \min_k |Y - c_k| \quad (19)$$

2.4. Geometric Interpretation and Conditional Probability

The geometric interpretation can also be expressed in terms of active train positions. For a cross-passage at position c_k , a train position is active when the train overlaps the tolerance zone around the cross-passage.

The tolerance distance ε links the fire-and-evacuation assessment with the geometric-probabilistic model. It is not derived from the geometric model itself. In this study, $\varepsilon = 37 \text{ m}$ is adopted from the Czech HSR fire-and-evacuation scenario assessment [20] and is interpreted as a scenario-dependent longitudinal thermal-effect distance around an evacuation interface. It is not a flame length, a point-source radiation distance, or a universal tunnel constant. This interpretation is consistent with the tunnel fire literature showing that heat flux and ceiling-gas temperature depend on heat release rate, tunnel geometry, ventilation conditions, smoke-layer development, heat losses to the tunnel structure, blockage, and the position of the fire relative to the train and evacuation route [1,8,19–21].

The physical basis of ε is the combined radiative-convective exposure near a cross-passage or portal. This exposure may include direct flame radiation, radiation from the hot smoke layer, convective heating by hot gases and ceiling-jet flow, re-radiation from heated tunnel surfaces, and local modification of the thermal field by train blockage and ventilation [21–24]. Therefore, ε is treated as a scenario-dependent thermal-effect distance rather than as a purely geometrical distance from the flame.

The reference threshold was taken as the long-duration evacuation heat-flux criterion $q'' = 2.5 \text{ kW} \cdot \text{m}^{-2}$ [8]. The corresponding effective ceiling-gas temperature was estimated using the hot-layer radiation relation $q'' = 0.68\sigma(T_{cf}^4 - T_0^4)$, where σ is the Stefan–Boltzmann constant and $T_0 = 293 \text{ K}$. For $q'' = 2.5 \text{ kW} \cdot \text{m}^{-2}$, this gives $T_{cf} \approx 518 \text{ K}$, i.e., approximately 245°C , and $\Delta T_c \approx 225 \text{ K}$ (see Table 2) [25,26].

The downstream distance corresponding to this threshold was checked using the longitudinal ceiling-gas temperature decay relation reported by Fan et al. [27]: $\Delta T_c / \Delta T_{c, \max} = 0.57 \cdot \exp(-0.13 \cdot x/H) + 0.43 \cdot \exp(-0.021 \cdot x/H)$, where x is the longitudinal distance from the fire source, H is the tunnel height, ΔT_c is the local excess ceiling-gas temperature, and $\Delta T_{c, \max}$ is the maximum excess ceiling-gas temperature near the fire source (see Table 3).

Table 2. Equivalent effective ceiling-gas temperature for selected incident heat-flux levels, calculated from $q'' = 0.68\sigma(T_{cf}^4 - T_0^4)$, $T_0 = 293 \text{ K}$.

q'' [kW·m ⁻²]	T_{cf} [K]	T_{cf} [°C]
1.5	464	191
2.0	493	220
2.5	518	245
3.0	540	267
4.0	577	304
5.0	609	335

Table 3. Engineering check of the distance to the $2.5 \text{ kW} \cdot \text{m}^{-2}$ heat-flux threshold using the ceiling-gas temperature decay relation.

$\Delta T_{c, \max}$ [K]	Approx. Maximum Ceiling-Gas Temperature [°C]	x/H for $q'' = 2.5 \text{ kW} \cdot \text{m}^{-2}$ -	x for $H = 4.5 \text{ m}$ [m]	x for $H = 6.5 \text{ m}$ [m]
300	320	3.70	17	24
350	370	5.94	27	39
400	420	8.07	36	52
450	470	12.18	55	79

For representative railway tunnel heights and plausible maximum excess ceiling-gas temperatures, this relation yields threshold distances on the order of several tens of meters. Because ε directly controls the width of the critical zone, a sensitivity analysis was defined for $\varepsilon = 25 \text{ m}$, 37 m , and 50 m . The resulting effect on geometric probability and critical traffic intensity is reported in the Results. The reference value $\varepsilon = 37 \text{ m}$ represents the adopted HSR scenario, while the lower and upper values were used to test the robustness of the geometric probability and the derived critical traffic intensity. In the central engineering case, $H \approx 6 \text{ m}$ and $\Delta T_{c, \max} \approx 350 \text{ K}$ yield $x \approx 36 \text{ m}$, consistent with the adopted $\varepsilon = 37 \text{ m}$. The value is therefore physically plausible for the adopted 20 MW HSR scenario [20], but it remains scenario dependent. Its influence is evaluated by sensitivity analysis in the Discussion.

This condition is given in Equation (20), and the corresponding interval of active train positions is given in Equation (21). For one cross-passage, the active length is $L + 2\varepsilon$, Equation (22). In the finite tunnel, the active train-position set is obtained by taking the union of these intervals for all cross-passages and restricting it to the admissible stopping domain, Equation (23). This identifies the train positions for which the event A_ε can occur.

$$[X, X + L] \cap [c_k - \varepsilon, c_k + \varepsilon] \neq \emptyset \quad (20)$$

$$X \in [c_k - \varepsilon - L, c_k + \varepsilon] \quad (21)$$

$$\ell_{act} = L + 2\varepsilon \quad (22)$$

$$\mathcal{A}_{tun} = \left(\bigcup_k [c_k - \varepsilon - L, c_k + \varepsilon] \right) \cap [0, T - L] \quad (23)$$

The finite and periodic formulations describe the same geometry at different levels. The finite model retains the actual tunnel boundaries, while the periodic model describes the repeated cross-passage pattern away from portals. The train-position density is given in Equation (24). The phase variable R , Equation (25), represents the train position within one spacing period, with density given in Equation (26). The fire-position density follows from convolution, Equation (27), and the periodic fire-position variable is defined in Equation (28).

$$f_X(x) = \frac{1}{T - L} 1_{[0, T-L]}(x) \quad (24)$$

$$R = X \bmod s \quad (25)$$

$$f_R(r) = \frac{1}{s} 1_{[0, s)}(r) \quad (26)$$

$$f_Y(y) = (f_X * f_U)(y) \quad (27)$$

$$Z = Y \bmod s \quad (28)$$

The same probability can be written as an average over fixed train positions. For a given train position $X = x$, the overlap length between the train and the tolerance zone around cross-passage c_k is $h_k(x)$, Equation (29). Since the fire origin is uniformly distributed along the train, the conditional probability for this train position is $p(x)$, Equation (30). The total probability π is obtained by averaging $p(x)$ over all admissible train positions, Equation (31). This form shows directly how individual train positions contribute to the overall probability.

$$h_k(x) = \lambda([x, x + L] \cap [c_k - \varepsilon, c_k + \varepsilon]) \quad (29)$$

$$p(x) = \frac{1}{L} \sum_k h_k(x) \quad (30)$$

$$\pi = \int_0^{T-L} p(x) f_X(x) dx \quad (31)$$

2.5. Acceptance Criterion and Hypothesis Decision

The acceptance criterion links geometric probability to collective risk through annual scenario frequency. The probability π was first calculated as a geometric quantity and then combined with the representative railway-vehicle fire frequency from Table 1. Because the assessment is framed within the EU interoperability and SRT TSI context, the representative input was defined as the European median fire frequency, $\lambda_{sig,EU}$. This value was scaled to the tunnel length, Equation (32). The Dutch F/N relationship was used as an external collective-risk reference, Equation (33), and was scaled to the same tunnel length, Equa-

tion (34). The annual scenario frequency was then calculated from the tunnel fire frequency, geometric probability, and annual traffic intensity, Equation (35). The decision condition is satisfied when this annual scenario frequency does not exceed the scaled F/N criterion, Equation (36). The derived value π_{lim} is retained only as a probability-equivalent quantity corresponding to the selected fire-frequency input and F/N criterion, Equation (37). It is not used as the primary decision variable; the practical decision is made through the corresponding critical traffic intensity n_{crit} .

The consequence parameter N was not treated as a deterministic number of fatalities. It represents the number of evacuees exposed to critically reduced visibility during evacuation in the selected one-track tunnel scenarios. The values $N_{200} = 28$ and $N_{400} = 97$ were taken from a separate evacuation assessment, in which visibility below 1.0 m was used as the critical condition because it strongly limits self-rescue by reducing orientation, walking speed, and local movement near the safe area. These consequence indicators were not calculated by the present geometric-probabilistic model but transferred from a Czech HSR fire-and-evacuation assessment [20], which evaluated visibility, temperature, heat flux, CO, CO₂, train configuration, occupancy, and fire and ventilation scenarios. The underlying FDS model represented a single-track railway tunnel with a cross-section of 9.0×7.5 m and a modeled length of approximately 710 m. The model included the tunnel tube, the train, and one cross-passage. The assessed scenario used a 20 MW design fire located in the first car of the train, with a time-dependent heat-release-rate curve reaching full power after 1200 s. The total simulation time was 1800 s. The train position was selected so that the fire occurred near the closest cross-passage, with a cross-passage spacing of 500 m. Boundary conditions included longitudinal airflow of $1.0 \text{ m}\cdot\text{s}^{-1}$, ambient temperature of 10°C , and relative humidity of 70%.

In this paper, N is the number of evacuees with visibility below 1.0 m, used as an exposure-based indicator for screening, not as a fatality estimate. The decision condition was applied to the upper confidence bound of the Monte Carlo estimate (Equation (38)) rather than to the point estimate alone. This provides a conservative numerical check of geometric probability. The Monte Carlo simulation verifies the analytical implementation of π ; it does not validate the physical fire, smoke, evacuation, or operational assumptions.

$$\lambda_{\text{sig,tun}} = \lambda_{\text{sig,EU}} \frac{T}{1000} \quad (32)$$

$$F_{\text{lim}}(N) = \frac{0.03}{N^2} \quad (33)$$

$$F_{\text{lim,tun}}(N) = \frac{T}{1000} \frac{0.03}{N^2} \quad (34)$$

$$F_{\text{sc}} = \lambda_{\text{sig,tun}} \pi \quad (35)$$

$$F_{\text{sc}} \leq F_{\text{lim,tun}}(N) \quad (36)$$

2.6. Conversion of the Acceptance Criterion into Traffic Intensity

The acceptance criterion was also expressed in terms of railway traffic intensity. This conversion does not introduce a new probability model or redefine the geometric probability π . The value of π remains fixed by tunnel geometry, train length, cross-passage spacing, and tolerance distance. The only variable is the number of train passages through the tunnel.

For one train passage through the 5 km tunnel, the fire-frequency contribution is given by Equation (39), using the European median fire frequency of $0.01455 \times 10^{-6} \text{ tr}^{-1}\cdot\text{km}^{-1}$. For n train passages per year, the annual scenario frequency is calculated by Equation (40). The critical number of annual train passages is reached when this frequency equals or exceeds the scaled acceptance criterion, Equation (41). The corresponding value n_{crit} is obtained by rounding up and is also expressed as an average number of trains per day.

This conversion was applied to the two analyzed train configurations, $L_{200} = 200$ m with $N_{200} = 28$ and $L_{400} = 400$ m with $N_{400} = 97$.

$$\lambda_{1tr,5km} = 0.01455 \times 10^{-6} \times 5 = 7.275 \times 10^{-8} tr^{-1} \quad (37)$$

$$F_{sc}(n) = n \lambda_{1tr,5km} \pi \quad (38)$$

$$F_{sc}(n) \geq F_{lim,tun}(N) \quad (39)$$

$$n_{crit} = \frac{F_{lim,tun}(N)}{\lambda_{1tr,5km} \pi} \quad (40)$$

$$n_{day} = \frac{n_{crit}}{365} \quad (41)$$

3. Results

3.1. Constants and Results Summary

The results are reported for the reference tolerance distance $\varepsilon = 37$ m. Two train variants were evaluated: $L = 200$ m and $L = 400$ m. The consequence indicators transferred from the evacuation assessment were $N = 28$ for the 200 m train and $N = 97$ for the 400 m train. These values represent the number of people exposed to visibility below 1.0 m in the corresponding evacuation scenarios. The finite-domain model includes the tunnel portals as boundaries of the spatial domain. The adverse blockage itself is evaluated for the nine internal cross-passages located between 500 m and 4500 m. Table 4 summarizes the probabilities of adverse geometric configurations and the corresponding annual scenario frequencies for a single train passage through the 5 km tunnel section. The representative passenger-train fire frequency used in the calculation was $\lambda = 0.01455 \times 10^{-6} tr^{-1} \cdot km^{-1}$. The sensitivity analysis for $\varepsilon = 25$ m, 37 m, and 50 m is summarized in Table 5. As expected, a larger ε increases the geometric probability and decreases the corresponding critical traffic intensity. The 400 m train variant remains the more restrictive case throughout the tested interval.

Table 4. Geometric probabilities and scenario frequencies for $\varepsilon = 37$ m.

Train Length L	Passenger Load	Consequence Indicator N	Geometric Probability π	Scenario Frequency Per Train Passage Through 5 km Tunnel
[m]	[-]	[-]	[-]	[-]
200	420	28	0.13875	1.02×10^{-8}
400	840	97	0.14478	1.06×10^{-8}

Table 5. Sensitivity of the geometric probability and critical traffic intensity to the tolerance distance ε .

Train Variant	ε	π	Scenario Frequency Per Train in 5 km Tunnel	n_{crit}	n_{crit}
[m]	[-]	[-]	[-]	[-]	[-]
200	25	0.09375	6.82×10^{-9}	28,053	76.9
200	37	0.13875	1.01×10^{-8}	18,955	51.9
200	50	0.18750	1.36×10^{-8}	14,026	38.4
400	25	0.09783	7.12×10^{-9}	2240	6.1
400	37	0.14478	1.05×10^{-8}	1514	4.1
400	50	0.19565	1.42×10^{-8}	1120	3.1

The Monte Carlo calculation confirmed the analytical probabilities within the sampling error. It was used only as a numerical verification of geometric model implementation.

Table 6 gives the critical traffic intensities obtained by coupling the scenario frequency with the Dutch F/N criterion for a 5 km tunnel section.

Table 6. Critical traffic intensities derived from the Dutch F/N criterion.

Train Length L	Dutch Criterion $F_{lim}(N)$	Critical Traffic Intensity n_{crit}	Critical Traffic Intensity n_{crit}
[m]	[yr ⁻¹]	[tr·yr ⁻¹]	[tr·day ⁻¹]
200	1.91×10^{-4}	18,955	51.9
400	1.59×10^{-5}	1514	4.1

For the 200 m train variant, the critical traffic intensity is approximately 51 train passages per day. For the 400 m train variant, the critical traffic intensity decreases to approximately four train passages per day because of the higher consequence indicator. The 400 m train variant is therefore the more restrictive case under the adopted F/N criterion.

3.2. Deterministic Solution, Active Lengths, and Finite-Tunnel Effects

The deterministic finite-domain solution was evaluated for the nine internal cross-passages, while the tunnel portals define the finite spatial domain of the convolution. For the reference tolerance distance $\varepsilon = 37$ m, the adverse geometric configuration probability is $\pi = 0.13875$ for the 200 m train and $\pi = 0.14478$ for the 400 m train. The entrance and exit effects shown in these figures represent finite-domain convolution effects caused by the bounded tunnel domain as the train enters and leaves the admissible position interval. The corresponding probability-density distributions and active intervals are shown in Figure 2 for the 200 m train and in Figure 3 for the 400 m train. The periodic approximation, which neglects finite-domain boundary effects, gives $\pi_{per} = 0.14800$ for both train lengths. The finite-domain probabilities are therefore lower than the periodic approximation of 0.00925 for the 200 m train and of 0.00322 for the 400 m train. The smaller difference for the 400 m train shows that the longer train approaches the periodic approximation more closely. This is expected because the longer train occupies a larger active position interval relative to the 500 m spacing of evacuation interfaces. The finite-tunnel effect is therefore more pronounced for the 200 m train variant.

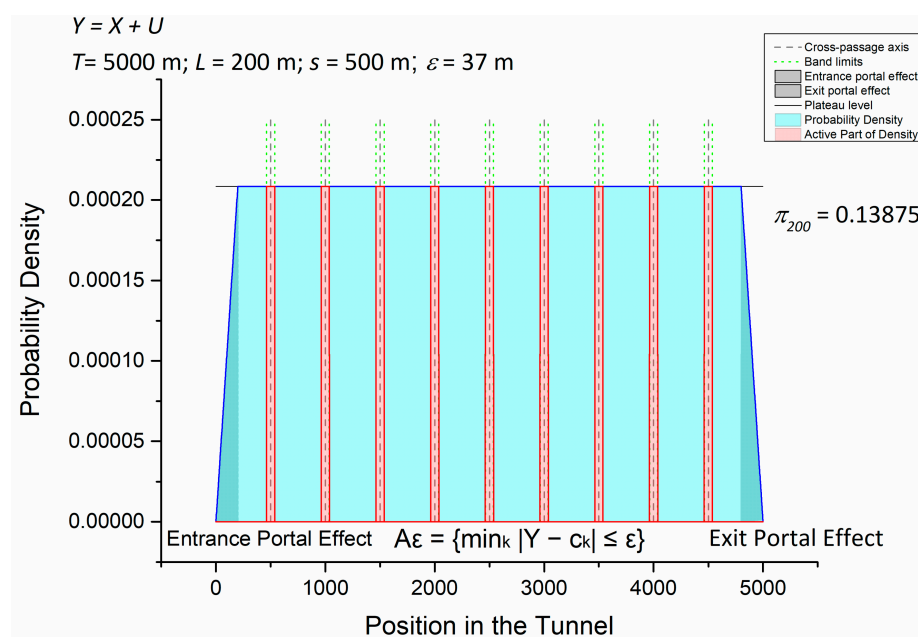


Figure 2. Probability density of the final fire position for the 200 m train variant. Red bands mark the tolerance zones around the nine internal cross-passages, where the event $A_\varepsilon = \{\min_k |Y - c_k| \leq \varepsilon\}$

occurs. The resulting probability for the internal cross-passage blockage event is $\pi_{200} = 0.13875$. The shaded entrance and exit portal regions illustrate finite-domain boundary effects; if the portals are additionally treated as boundary evacuation interfaces, the probability increases to $\pi_{200} = 0.14018$, corresponding to an additional boundary contribution of approximately 0.00143.

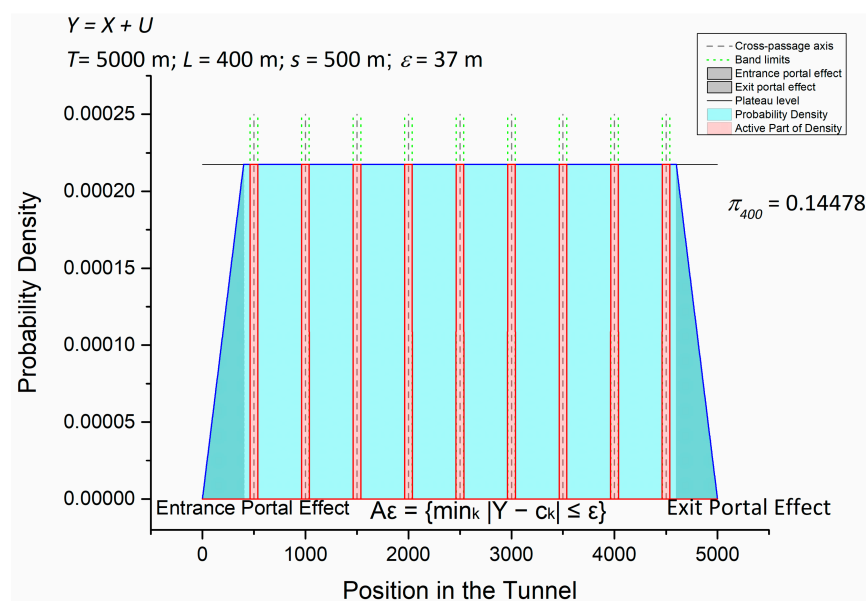


Figure 3. Probability density of the final fire position for the 400 m train variant. Red bands mark the tolerance zones around the nine internal cross-passages, where the event $A\varepsilon = \{\min_k |Y - c_k| \leq \varepsilon\}$ occurs. The resulting probability for the internal cross-passage blockage event is $\pi_{400} = 0.14478$. The shaded entrance and exit portal regions illustrate finite-domain boundary effects; if the portals are additionally treated as boundary evacuation interfaces, the probability increases to $\pi_{400} = 0.14553$, corresponding to an additional boundary contribution of approximately 0.00075.

3.3. Monte Carlo Verification

Numerical verification was performed with 10^8 Monte Carlo realizations for each train length. The same number of realizations was used for both variants. Stability was assessed using the running cumulative estimate and a block-based analysis with 100 blocks of 10^6 realizations. Stabilization was defined as the point at which the running estimate remained within the final 95% confidence interval for the remainder of the simulation. According to this criterion, the running estimate stabilized after approximately 21 million realizations for the 200 m train and after approximately 15 million realizations for the 400 m train. For the 200 m train, the Monte Carlo estimate was $\hat{\pi} = 0.13874457$, with a 95% confidence interval of [0.13867682, 0.13881232]. For the 400 m train, the Monte Carlo estimate was $\hat{\pi} = 0.14479965$, with a 95% confidence interval of [0.14473068, 0.14486862]. In both cases, the deterministic finite-domain value was within the confidence interval. The Monte Carlo simulation confirms the numerical implementation of the analytical geometric model. The different stabilization points for the 200 m and 400 m variants are due to the stochastic path of the estimate and the stabilization criterion based on the confidence interval, not different physical behavior. Monte Carlo verification confirms the implementation but does not validate fire, smoke, operational, or evacuation assumptions.

3.4. Conditional Probability, Acceptance Criterion, and Representative Scenarios

The conditional-probability evaluation quantifies the extent to which individual train-stopping positions contribute to the occurrence of the adverse geometric event. For the 200 m train, the maximum local conditional probability is $p_{\max} = 0.37$, and the mean conditional probability within the active positions is $\bar{p}_{\text{act}} = 0.27007$. For the 400 m train, the

corresponding values are $p_{max} = 0.185$ and $\bar{p}_{act} = 0.15612$. The lower local conditional probabilities for the 400 m train result from its greater length: the same tolerance zone represents a smaller fraction of the train. However, the longer train also occupies a larger active position interval relative to the 500 m cross-passage spacing. As a result, the overall geometric probability remains slightly higher for the 400 m train, despite its lower local conditional probability. The two evaluated variants, therefore, represent different combinations of geometry and consequence. The 200 m train has a lower consequence indicator ($N = 28$) and a critical traffic intensity of approximately 51 train passages per day. The 400 m train has a higher consequence indicator ($N = 97$) and meets the selected Dutch F/N criterion at approximately four train passages per day. The difference between the variants is therefore governed mainly by the consequence level and traffic intensity, not by a large difference in geometric probability.

3.5. Hypothesis Verification Based on Critical Traffic Intensity

The hypothesis decision was made using the critical traffic intensity derived from the selected Dutch F/N criterion as shown in Figure 4. The geometric probability π was therefore not interpreted as an independent acceptability threshold. Instead, the screening condition was considered satisfied only for traffic intensities below the corresponding critical number of train passages. For the 200 m train variant with $N = 28$, $\pi = 0.13875$ gives a critical traffic intensity of $n_{crit} = 18,955$ train passages per year, corresponding to approximately 51.9 train passages per day. For the 400 m train variant with $N = 97$, $\pi = 0.14478$ gives $n_{crit} = 1514$ train passages per year, corresponding to approximately 4.1 train passages per day. The screening interpretation is therefore conditional and applies only to traffic intensities below these thresholds. For the 200 m train, the limit is relatively high, at about 52 train passages per day. For the 400 m train, the limit is much lower, about four train passages per day, because the larger consequence indicator substantially reduces the admissible frequency under the F/N criterion. The 400 m train variant is therefore the more restrictive case.

Comparison of scenario frequency with selected societal-risk acceptance criteria

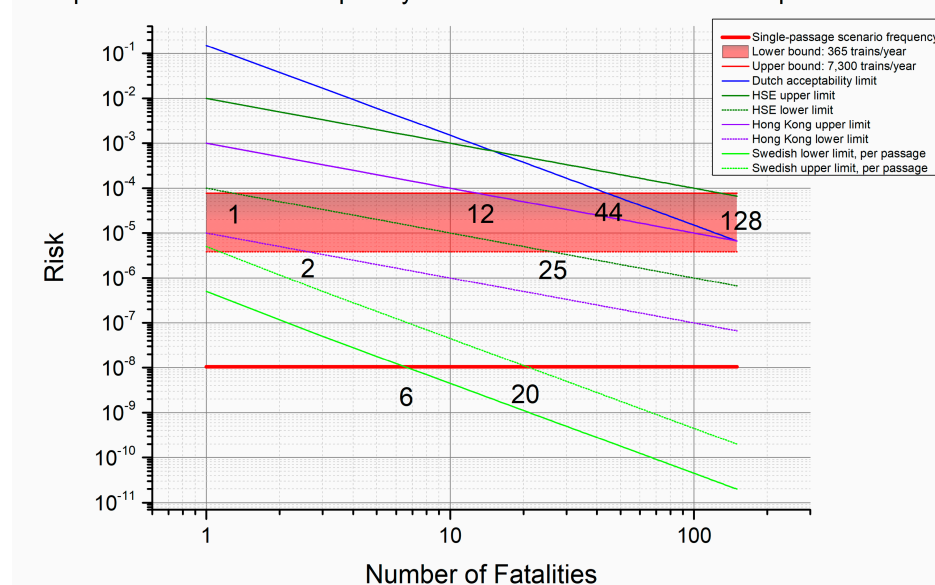


Figure 4. Comparison of scenario frequency with selected societal-risk acceptance criteria. The red line shows the single-passage scenario frequency, and the shaded band indicates the corresponding annual frequency range for 365–7300 train passages per year. Dutch, HSE, Hong Kong, and Swedish criteria are included for comparison. The numerical labels in the figure denote the consequence size N used in the F/N assessment. In this study, N is interpreted as the number of affected persons transferred from the evacuation assessment, not as an observed fatality count.

4. Discussion

4.1. Scope and Role of the Model

The model addresses a deliberately narrow design question: how often a train fire occurs in a position where the nearest cross-passage may become unavailable for self-evacuation. This narrow scope is intentional [27,28]. Full quantitative risk assessment of railway tunnels usually combines initiating events, fire development, detection, ventilation, smoke spread, evacuation, human exposure, and consequence modeling, often through event-tree or bow-tie logic [12,15,29]. The present model does not replace CFD modeling, evacuation simulation, or full QRA. It isolates one geometrically quantifiable component of the risk chain: the probability that the final fire position lies within a defined tolerance distance from an evacuation interface.

The method should therefore be interpreted as a screening layer. It identifies whether the “fire near a cross-passage” configuration is marginal or warrants further detailed CFD and evacuation assessments. This is consistent with tunnel-risk approaches in which scenario selection, fire modeling, evacuation modeling, and risk representation are treated as interconnected but separately defined steps [12,29].

The SRT TSI requirement for cross-passages at intervals not exceeding 500 m should therefore be treated as a minimum design baseline, not as proof that every local adverse configuration is negligible [5]. The Common Safety Method framework also allows safety to be demonstrated by comparison with reference systems, codes of practice, or explicit risk estimation [30,31]. Consequently, even where the 500 m spacing requirement is satisfied, the local loss of cross-passage usability should still be assessed in terms of frequency, consequences, and the selected acceptance framework.

4.2. Interpretation of Geometric Probability

For the reference homogeneous model with $\varepsilon = 37$ m, the finite-domain probabilities are $\pi_{200} = 0.13875$ for the 200 m train and $\pi_{400} = 0.14478$ for the 400 m train. The absolute difference is 0.00603, corresponding to a relative increase of approximately 4.35%. Train length alone is therefore not the dominant driver of geometric probability.

This result follows from the structure of the model. A longer train occupies a larger active position interval relative to the 500 m cross-passage spacing. At the same time, the same tolerance zone represents a smaller fraction of the train length. The 400 m train, therefore, has a slightly higher overall geometric probability, while its local conditional probabilities are lower than those of the 200 m train. The increase in π is caused mainly by the larger filling of the active position space, not by a higher local conditional probability.

The assumption of a uniform fire-origin distribution is useful as a transparent first-order screening assumption. It avoids unsupported preferences for any train section, making the result reproducible. It should not, however, be interpreted as a final vehicle-specific failure-frequency model. In a real train, ignition probability is unlikely to be uniformly distributed along the entire train length. Technical compartments, traction equipment, converters, transformers, batteries, HVAC units, luggage spaces, toilets, catering modules, and passenger areas may have different ignition probabilities [21,25].

A non-homogeneous fire-origin distribution may therefore change the result in either direction. In some parts of the train, the probability of fire origin may be higher than in the homogeneous model; in other parts, it may be lower. If the higher-probability sections more often coincide with critical zones around cross-passages, the resulting π would increase, and the operational reserve, expressed by n_{crit} , would decrease. Conversely, if higher-probability sections are typically located away from the critical zones, π could decrease, and the operational reserve could increase. The effect of a non-homogeneous distribution is therefore not known a priori. It requires vehicle-specific fire-origin data and should be

treated as a future refinement rather than a demonstrated conclusion of the present model. Introducing a non-uniform distribution without such data would create an unsupported impression of precision and was therefore not used in the reference screening calculation.

4.3. Hypothesis Decision Based on Critical Traffic Intensity

The hypothesis decision should be based on critical traffic intensity, not on geometric probability alone. The geometric probability π describes how often an adverse spatial configuration occurs. It does not, by itself, determine whether the scenario is acceptable. Acceptability also depends on the significant-fire frequency, tunnel length, traffic intensity, consequence size, and the selected societal-risk criterion.

For the reference calculation, the significant passenger-train fire frequency is $\lambda = 0.01455 \times 10^{-6} \text{ tr}^{-1} \cdot \text{km}^{-1}$. For one train passage through a 5 km tunnel section, this gives $\lambda_{1\text{tr},5\text{km}} = 7.275 \times 10^{-8} \text{ yr}^{-1}$. Using the Dutch criterion $0.03/N^2$ per km per year [14], the critical traffic intensity is approximately 18,955 train passages per year for the 200 m train, corresponding to about 51.9 train passages per day. For the 400 m train, the critical traffic intensity is approximately 1514 train passages per year, corresponding to about 4.1 train passages per day.

The difference between the two variants is therefore governed mainly by consequence size, not by geometric probability. The 400 m train has a substantially higher consequence indicator, $N_{400} = 97$, than the 200 m train, $N_{200} = 28$. Under an F/N criterion, a larger value of N strongly reduces the admissible frequency. The 400 m train variant is therefore the more restrictive case, although its geometric probability is only slightly higher.

The hypothesis that the adverse configuration is negligible is therefore supported only conditionally. For the 200 m train, it is supported below approximately 18,955 train passages per year through the assessed 5 km tunnel section. For the 400 m train, support is only provided below approximately 1514 train passages per year. Above these values, the local loss of the nearest cross-passage should not be treated as negligible under the Dutch criterion.

The consequence value N should also be interpreted carefully. In this study, N is not a directly observed number of fatalities. It is a consequence indicator transferred from the evacuation assessment and represents the number of affected persons under the selected exposure condition. This distinction is important because F/N criteria are often formulated for fatalities, whereas evacuation analysis may provide intermediate indicators of exposure or tenability. The present use of N should therefore be understood as a screening transformation of the evacuation result, not as a direct fatality prediction [19].

4.4. Sensitivity to the Acceptance Framework

The conclusion regarding acceptability depends on the selected societal risk framework. The Dutch criterion, used as the primary benchmark, yields a single decision boundary, whereas other F/N -based approaches use different slopes, normalizations, and acceptance bands. The same scenario may therefore be acceptable under one framework, fall into an intermediate or ALARP region under another, and approach the unacceptable region under a stricter criterion.

The Swedish Trafikverket methodology uses a different risk metric and an ALARP-oriented interpretation, with risk expressed per train-kilometer before conversion to an F/N representation [8,32]. This makes the Swedish approach more restrictive for some high-consequence scenarios. The HSE and Hong Kong approaches also use lower and upper societal-risk bands rather than a single acceptance curve [33,34]. F/N -based comparison is therefore useful not as a universal pass/fail decision but as a way to show how dependent the result is on the selected assessment framework.

Table 7 compares the two train variants with the Dutch criterion and with Swedish, HSE, and Hong Kong societal-risk bands. The comparison is indicative, as the frameworks differ in their policy backgrounds, risk metrics, normalization, and interpretations of ALARP. The Dutch criterion is evaluated as $0.03/N^2$ per km per year and converted to the 5 km tunnel section. The HSE comparison is expressed using the indicative lower and upper F/N bands $10^{-4}/N$ and $10^{-2}/N$ [33]. The Hong Kong comparison uses the lower acceptable and upper unacceptable bands $10^{-5}/N^2$ and $10^{-3}/N^2$ [34].

Table 7. Comparison of the assessed scenario with selected societal-risk acceptance bands.

Framework	Band/Criterion	Limit for $N = 28$ [yr ⁻¹]	Limit for $N = 97$ [yr ⁻¹]	n_{crit} for 200 m [tr·yr ⁻¹]	n_{crit} for 400 m [tr·yr ⁻¹]
Dutch	$5 \times 0.03/N^2$	1.91×10^{-4}	1.59×10^{-5}	18,955	1514
HSE lower band	$10^{-4}/N$	3.57×10^{-6}	1.03×10^{-6}	354	98
HSE upper band	$10^{-2}/N$	3.57×10^{-4}	1.03×10^{-4}	35,386	9788
Hong Kong lower band	$10^{-5}/N^2$	1.28×10^{-8}	1.06×10^{-9}	1.3	0.1
Hong Kong upper band	$10^{-3}/N^2$	1.28×10^{-6}	1.06×10^{-7}	126	10
Swedish lower band	Lower ALARP boundary converted to the assessed 5 km tunnel section	5.28×10^{-8}	4.40×10^{-11}	0.05	0.004
Swedish upper ALARP band	Upper ALARP boundary converted to the assessed 5 km tunnel section	5.28×10^{-8}	4.40×10^{-9}	5.2	0.42

The comparison shows a clear hierarchy of restrictiveness among the selected societal-risk frameworks. The Dutch criterion gives the largest operational reserve. Under this criterion, the critical traffic intensity is approximately 18,955 train passages per year for the 200 m train and 1514 train passages per year for the 400 m train. The HSE bands provide intermediate interpretation. The lower HSE band is reached much earlier, at approximately 354 train passages per year for the 200 m train and 98 for the 400 m train. In contrast, the upper HSE band is reached only at much higher intensities, approximately 35,386 and 9788 train passages per year, respectively.

The Hong Kong and Swedish frameworks are more restrictive. Under the Hong Kong lower band, the 400 m train exceeds the acceptable boundary even for one annual passage through the assessed 5 km tunnel section. In comparison, the 200 m train reaches this boundary at approximately 1.3 train passages per year. The Hong Kong upper band is less restrictive than its lower acceptable boundary but still gives substantially smaller operational reserves than the Dutch and HSE upper bands: approximately 126 train passages per year for the 200 m train and 10 train passages per year for the 400 m train.

The Swedish-converted ALARP bands provide the strictest interpretation in this comparison. The lower Swedish band is exceeded for both train variants, even with fewer than one annual passage. The upper Swedish ALARP boundary is reached at approximately 5.2 train passages per year for the 200 m train and 0.42 for the 400 m train. This means that under the Swedish upper ALARP boundary, the 400 m train variant would already exceed the criterion for one annual passage through the assessed tunnel section.

Overall, the same geometric scenario changes its interpretation substantially depending on the selected acceptance framework. The 400 m train meets the Dutch criterion at its calculated critical traffic intensity, but it becomes much more problematic under the Hong Kong and, especially, the Swedish frameworks. The result should therefore be presented as framework-dependent acceptability, not as a universal statement that the configuration is negligible.

4.5. Uncertainty of ε and Fire-Frequency Data

The parameter ε is a governing input of the model. It represents the longitudinal distance from a cross-passage within which the cross-passage may be thermally compromised for self-evacuation. It should not be treated as a universal constant, a flame length, or a simple point-source radiation distance. Tunnel tenability depends on heat release rate, tunnel width and height, longitudinal ventilation, blockage, smoke-layer development, heat losses to the lining, longitudinal gradient, and the position of occupants relative to the hot smoke layer [1,2,19,23,24,26].

The adopted value $\varepsilon = 37$ m is based on the reference Czech HSR fire-and-evacuation scenario [20]. It is physically plausible for the reference 20 MW HSR scenario and the selected tunnel configuration, but it should not be transferred automatically to all tunnels. For a defined family of similar high-speed railway tunnels with comparable profiles, linings, gradients, and ventilation assumptions, ε may be used as a family parameter if repeated modeling confirms that the thermal conditions remain within the same range. For different tunnel profiles, ventilation regimes, gradients, train types, or design fires, ε should be recalculated.

The design-fire assumption is also important. HRR values for high-speed train fires may vary with vehicle configuration, combustible load, ventilation conditions, and the involvement of technical or passenger compartments [25]. Since ε is derived from the expected thermal and smoke conditions, it is sensitive not only to tunnel geometry but also to the adopted design fire.

Fire-frequency data introduce a second major uncertainty. The representative value used here is suitable for screening, but European public safety statistics often aggregate events across vehicle categories, infrastructure types, and operational contexts. Such datasets do not always distinguish passengers from freight traffic, conventional from high-speed traffic, or minor fires from significant fire scenarios. ERA reports are useful for system-level safety monitoring. Still, they do not provide a sufficiently specific incidence rate for significant fires in modern high-speed passenger units operating in long tunnels [33,34].

This limitation is important because the critical traffic intensity is inversely proportional to the adopted fire frequency. For example, using the lower Japanese value of $0.0013 \times 10^{-6} \text{ tr}^{-1} \cdot \text{km}^{-1}$ would increase n_{crit} by approximately a factor of 11.2 compared with the reference median, whereas using the higher English value of $0.0572 \times 10^{-6} \text{ tr}^{-1} \cdot \text{km}^{-1}$ would reduce n_{crit} to approximately one-quarter of the reference value. If a lower significant-fire frequency is justified for a specific modern HSR fleet, the operational reserve increases. If a higher or more conservative frequency is adopted, the reserve decreases. The result is therefore not a fixed property of cross-passage spacing alone but a combined outcome of geometry, fire frequency, consequence, and the selected acceptance criterion.

4.6. Practical Implications and Further Work

The proposed method supports a two-step safety assessment. In the first step, the geometric-probabilistic model assesses whether the adverse spatial configuration is sufficiently frequent to matter. In the second step, the selected configurations are assessed by CFD and evacuation modeling to determine smoke development, heat exposure, visibility, ASET/RSET balance, and the number of exposed persons. This avoids two opposite errors: assuming that compliance with 500 m cross-passage spacing automatically makes the scenario negligible or performing detailed CFD and evacuation modeling for every possible train position without prior screening.

For the reference case, the 200 m train has a larger operational reserve under the Dutch criterion. The 400 m train is more restrictive because its consequence indicator is larger, not because its geometric probability is much higher. Under stricter frameworks,

especially the Hong Kong lower acceptable band, the same 400 m scenario may no longer be negligible even when it complies with the Dutch criterion. The design conclusion is therefore conditional: it applies only within the adopted assumptions on fire frequency, consequence definition, ε , and acceptance framework.

Further work should focus on four points. First, the homogeneous fire-origin distribution should be replaced by a mixed or vehicle-architecture-dependent distribution. Such a distribution may increase or decrease the resulting probability depending on the location of higher-risk train sections relative to cross-passages. Second, ε should be derived from repeated CFD-based thermal assessments and treated as a scenario-dependent parameter. Third, fire-frequency data should be separated by train category, operating context, and fire severity. Fourth, the model should be linked to an economic and operational assessment of possible mitigation measures, including shorter cross-passage spacing, improved detection, communication, ventilation control, evacuation guidance, and measures that reduce the number of exposed passengers. Future development should address input parameter uncertainty, stochastic modeling of variables, and transitioning from deterministic screening to linking uncertain inputs, system response, and safety criteria. Probabilistic methods in tunnel engineering show that input uncertainty can impact safety assessments, enabling more robust designs [35].

5. Conclusions

The study shows that a fire scenario near a tunnel cross-passage cannot be considered negligible solely because the tunnel satisfies the 500 m cross-passage spacing requirement. Its relevance depends on geometry, train length, occupancy, fire frequency, consequence size, and the selected societal-risk criterion. The deterministic convolution solution and Monte Carlo verification gave consistent results. For $\varepsilon = 37$ m, the adverse-configuration probabilities were similar for both train lengths: $\pi_{200} = 0.13875$ and $\pi_{400} = 0.14478$. The main difference between the variants is therefore not geometric probability itself but its combination with consequence and operational exposure. Under the Dutch criterion, the 200 m train with $N = 28$ gives a critical traffic intensity of about 18,955 train passages per year, or 51.9 per day. The 400 m train with $N = 97$ gives about 1514 train passages per year, or 4.1 per day. The 400 m variant is therefore the more restrictive case, mainly because the higher consequence reduces the admissible frequency under the F/N criterion. The screening condition is satisfied only under the calculated critical traffic intensities and the selected Dutch criterion. It should not be generalized to all traffic levels or to all acceptance frameworks. The comparison with HSE, Hong Kong, and Swedish criteria showed that the same scenario may be interpreted more restrictively, especially for the 400 m train.

The uniform fire-origin distribution should be treated as a screening assumption, not as a final vehicle-specific model. A non-homogeneous distribution may increase or decrease the resulting probability depending on whether higher-risk train sections coincide with the critical zones around cross-passages. The operational reserve expressed by n_{crit} may therefore also decrease or increase. The parameter ε is also scenario dependent. The adopted value $\varepsilon = 37$ m is suitable for the reference HSR scenario but depends on tunnel profiles, ventilation regimes, gradients, train types, or design fires; it requires separate verification. The proposed method can be used as a screening tool to identify configurations that require detailed CFD and evacuation modeling. Future work should focus on vehicle-specific fire-origin distributions, scenario-dependent values of ε , improved fire-frequency data for high-speed passenger trains, and comparison of design decisions across different societal-risk frameworks.

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Abbreviations/Nomenclature

Symbol	Meaning	Unit/Domain
A_ε	Event that the fire lies within the tolerance zone of a cross-passage, i.e., $D \leq \varepsilon$	–
$\mathcal{A}_{tun}$	Active set of admissible train rear-end positions in the finite tunnel	set of intervals
C	Set of cross-passage positions	m
c_k	Position of the k-th cross-passage	m
D	Distance from the fire position to the nearest cross-passage	m
ε	Tolerance distance from the cross-passage axis	m
2ε	Total width of the tolerance zone around one cross-passage	m
$f_R(r)$	Probability density function of R	m^{-1}
$f_U(u)$	Probability density function of U	m^{-1}
$f_X(x)$	Probability density function of X	m^{-1}
$f_Y(y)$	Probability density function of Y	m^{-1}
$f_Z(z)$	Probability density function of Z	m^{-1}
$F_{lim}(N)$	Limit frequency according to the reference F/N criterion per kilometer	$yr^{-1} \cdot km^{-1}$
$F_{lim,200}$	Limit frequency for N_{200}	yr^{-1}
$F_{lim,400}$	Limit frequency for N_{400}	yr^{-1}
$F_{lim,tun}(N)$	Limit frequency scaled to tunnel length T	yr^{-1}
F_{sc}	Annual frequency of the assessed scenario	yr^{-1}
$F_{sc}(n)$	Annual scenario frequency for n train passages per year	yr^{-1}
$F_{sc,200}$	Annual scenario frequency for the 200 m train variant	yr^{-1}
$F_{sc,400}$	Annual scenario frequency for the 400 m train variant	yr^{-1}
$F_{sc,200}^U$	Scenario frequency based on the upper confidence bound for the 200 m variant	yr^{-1}
$F_{sc,400}^U$	Scenario frequency based on the upper confidence bound for the 400 m variant	yr^{-1}
$h_k(x)$	Length of overlap between the train and the tolerance zone of the k-th cross-passage	m
i	Monte Carlo run index	–
I_i	Indicator variable for event A_ε in the i-th Monte Carlo run	0 or 1
k	Cross-passage index	–
L	Train length	m
L_{200}	Length of the shorter train variant	m
L_{400}	Length of the longer train variant	m
ℓ_{act}	Active length relative to one cross-passage	m
$\lambda_{sig,EU}$	Representative fire occurrence frequency per train-kilometer	$tr^{-1} \cdot km^{-1}$
$\lambda_{sig,tun}$	Fire frequency scaled to tunnel length	depends on the definition
$\lambda_{1tr,5km}$	Fire-frequency contribution of one train passage through a 5 km tunnel	tr^{-1}

$\lambda(\cdot)$	Interval length measure	m
n	Number of train passages per year	tr·yr ⁻¹
n_{crit}	Critical annual traffic intensity at which the acceptance limit is reached or exceeded	tr·yr ⁻¹
$n_{crit,200}$	Critical annual traffic intensity for the 200 m train variant	tr·yr ⁻¹
$n_{crit,400}$	Critical annual traffic intensity for the 400 m train variant	tr·yr ⁻¹
n_{day}	Average daily traffic intensity	tr·day ⁻¹
$n_{day,200}$	Average daily traffic intensity for the 200 m train variant	tr·day ⁻¹
$n_{day,400}$	Average daily traffic intensity for the 400 m train variant	tr·day ⁻¹
N	Consequence parameter	persons
N_{200}	Consequence parameter for the 200 m train variant	persons
N_{400}	Consequence parameter for the 400 m train variant	persons
N_{MC}	Number of Monte Carlo runs	–
$p(x)$	Conditional probability that the fire lies in a tolerance zone for fixed train position $X = x$	–
$\bar{p}_{act,200}$	Mean conditional probability over active positions for the 200 m train variant	–
$\bar{p}_{act,400}$	Mean conditional probability over active positions for the 400 m train variant	–
$p_{max,200}$	Maximum local conditional probability for the 200 m train variant	–
$p_{max,400}$	Maximum local conditional probability for the 400 m train variant	–
R	Phase variable for the train rear-end position	m
s	Cross-passage spacing	m
$SE(\hat{\pi})$	Standard error of the Monte Carlo estimate	–
T	Tunnel length	m
U	Fire-origin position along the train	m
U_i	Fire-origin position in the i-th Monte Carlo run	m
X	Rear-end position of the train measured from the tunnel portal	m
X_i	Rear-end train position in the i-th Monte Carlo run	m
Y	Fire position in the tunnel	m
Y_i	Fire position in the i-th Monte Carlo run	m
Z	Phase variable for the fire position	m
$z_{1-\alpha}$	Quantile of the standard normal distribution	–
α	Significance level used for the confidence bound	–
π	Geometrical probability of event A_ϵ	–
$\hat{\pi}$	Monte Carlo estimate of π	–
$\hat{\pi}_n$	Sequential Monte Carlo estimate after n runs	–
π_{200}	Geometrical probability for the 200 m train variant	–
π_{400}	Geometrical probability for the 400 m train variant	–
π_{per}	Periodic-limit probability without portal effects	–
$\pi_{1-\alpha}^U$	Upper one-sided confidence bound for π	–
$\pi_{0.95,200}^U$	Upper 95% confidence bound for the 200 m train variant	–
$\pi_{0.95,400}^U$	Upper 95% confidence bound for the 400 m train variant	–

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