PERMISSIBILITY OF DANGEROUS GOODS TRAFFIC THROUGH AN URBAN TRAIN TUNNEL IN BELGRADE – A RISK STUDY

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ABSTRACT

Serbia and in particular Belgrade have been exposed to fundamental political, structural and economic changes for a period of several decades. Consequently, the ever changing boundary conditions are also reflected in the Belgrade railway network. A recent example of such an alteration is the closure of the railway bypass along the banks of the Sava river due to a large scale real estate project in 2018. As a consequence, dangerous goods (DG) trains running along the Save river are now rerouted through the Vračar tunnel, which is one of the crucial public transport lines in the heart of Belgrade city.

In order to assess the impact of the frequent DG traffic on the safety level of the suburban railway tunnel, a quantitative risk model has been developed and applied. The analysis showed that the additional risk posed by the transport of DG can be managed very effectively by the implementation of operational measures. The residual risk mainly arises from fires scenarios of passenger trains inside the tunnel tube aside the underground station, where technical systems to support evacuation are largely missing. Therefore, the implementation of measures such as emergency lighting & escape signage, escape walkways or emergency cross-passages show great potential to further improve tunnel safety beyond the risk of DG incidents.

Keywords: tunnel safety, dangerous goods, suburban railway, safety measures, risk model

1. INTRODUCTION

Without a metro system and with a heavily overloaded road network, the railway line 1 in central Belgrade serves as an important local public means of transport. To increase the efficiency and capacity of the passenger railway network, crucial parts of the lane had been designed and constructed underground the city centre. One important tunnel, connected to the surface with the central subway station “Vukov Spomenik”, is the Vračar tunnel. It is a 3.54 km long twin-tube tunnel which tubes are connected only at the station. At peak hours, hundreds of people are present at the station, which is located approximately in the middle of this tunnel.

In addition to passenger trains, also freight trains are directed underneath the city centre of Belgrade. DG trains leaving at high frequency from the chemical industrial area of Pančevo, north of Belgrade, are heading through the city, to the southern regions of Serbia. To separate passenger- and DG traffic, DG trains had been routed via a bypass along the banks of the Sava river. However, this bypass was closed down in summer 2018, as a large-scale real estate project – Belgrade Waterfront – is going to be realized in this area. Consequently, an alternative route had to be established. The route through the Vračar tunnel represents the most direct connection for the considered DG trains and is, apart from a large-scale rerouting of more than hundred kilometres, the only train connection from Pančevo to the south. Due to the closure of the freight train bypass and for the simple reason of missing alternatives, now - additional to usual freight trains - also DG transports are allowed to pass through the Vračar tunnel.

However, the transport of DG through urban areas, and in particular through tunnels with heavily frequented passenger traffic, is considered as very dangerous (UNECE, 2003). Even though industrial and economical needs are of great importance, passenger safety has to be treated at minimum with the same or still better with a higher interest.
To assess the potential risk arising from the transport of DG, a quantitative risk assessment study has been conducted for the urban “metro-like” railway tunnel. The expectable frequencies for DG incidents as well as “conventional” train incidents, like train fires or mechanical incidents, have been calculated based on incident data collected on the Serbian federal railway network. In combination with physical and physiological models, representing the effects of hazards on humans, risk values have been estimated. This allows to compare risk profiles according to the situation before and after the permission of DG trains through the Vračar tunnel. In addition to the risk assessment of the current situation, also the effectivity of additional risk mitigation measures has been investigated. The remainder of the present study focuses mainly on the respective results.

2. VRAČAR TUNNEL – RISK MODEL

2.1. Incident frequencies

Train incidents can potentially escalate to catastrophic events, in particular if DG are involved. Thus, the transportation of DG through a railway tunnel, mainly used for passenger traffic, has to be considered with specific attention and care. However, risk, per definition, is not determined by the incident consequences alone, but also by the likelihood of such an event, which is represented by the incident frequency. The release of DG can either be triggered by a preceding event (derailment, collision, fire) or by a technical failure of the DG vessel which then leads to a leakage. Thus four initial incidents were considered in the risk assessment:

- Train fire (passenger train, freight train),
- Train collision (with- and without at least one passenger train),
- Train derailment (passenger train, freight train),
- DG release due to a leaking vessel (freight train only).

For all eight event types, incident frequencies have been calculated according to the respective incident rates obtained from data on the whole Serbian railway network, and based on the traffic volume through the tunnel, see Table 1. Currently, 74 passenger trains per day, 8 freight trains per day and 7 DG trains per day are operated through the tunnel. In order to minimise statistical uncertainties, incident data for the years 2008 – 2017 collected on the whole Serbian railway network have been analysed.

Table 1: Average incident frequency for the Vračar tunnel.

Incident type	Passenger-train incident frequency $[incidents/year]$	Freight-train incident frequency $[incidents/year]$
Train fire	$f_{fire}^{passenger\ train} = 5.4 \times 10^{-2}$	$f_{fire}^{freight\ train} = 4.5 \times 10^{-2}$
Train collision	$f_{collision}^{passenger\ train} = 2.3 \times 10^{-3}$	$f_{collision}^{freight\ train} = 1.93 \times 10^{-3}$
Train derailment	$f_{derailment}^{passenger\ train} = 3.1 \times 10^{-2}$	$f_{derailment}^{freight\ train} = 6.2 \times 10^{-2}$
Leaking vessel	-	$f_{leaking\ vessel}^{freight\ train} = 3.1 \times 10^{-4}$

The probability of a DG incident inside the tunnel has been estimated by the probability that an initial incident (mechanical or fire) affects a DG wagon. With 30% of all train wagons actually carrying DG the total frequency of DG incidents can be calculated based on

$$f_{DG} = 0.30 \times \left(f_{fire}^{freight\ train} + f_{collision}^{freight\ train} + f_{derailment}^{freight\ train}\right) + f_{leaking\ vessel}^{freight\ train}$$

Equation 1: Frequency of DG incidents in the tunnel.

and results in $\mathbf{3.3 \times 10^{-2}}$ **DG incidents per year** or equivalently **one DG incident in 30 years.**

The frequency estimation is of course very conservative. Not every incident documented on the Serbian railway is severe enough to potentially cause a failure of a DG vessel. However, due to the potentially high risk on passengers in the tunnel, and to be precautious, this conservative values have been used without further modification for the frequency estimation in the Vračar tunnel.

Figure 1 depicts the volume of transported DG (RID-classes) via the now closed bypass from 2008 to 2018. According to this distribution five different possible DG scenarios have been identified: The **explosive scenario** according to the representative substance TNT; the **toxic gas scenario** according to chlorine; the **VCE** and **BLEVE scenarios** corresponding to propane and the **pool-fire scenario** arising from flammable liquids such as petrol and diesel.

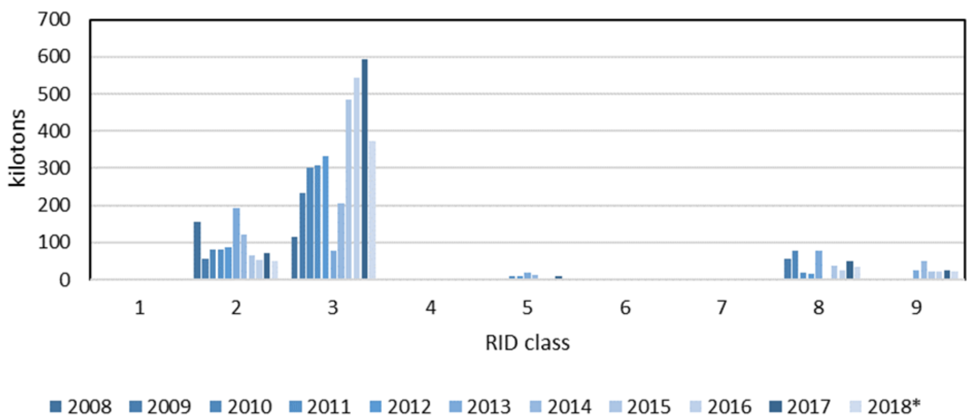


Figure 1: Volume of dangerous good transported via the bypass with respect to RID class.

In addition to freight-train incidents with an involvement of DG also conventional freight train scenarios (non-DG incidents) as well as pure passenger train incidents have been considered by means of an event-tree analysis. In total 208 different damage scenarios arising from 3 passenger-train event trees (fire, derailment, collision) and 4 freight-train event trees (fire, derailment, collision, leaking vessel) have been studied.

2.2. Consequence analysis

The central station "Vukov Spomenik" (length 225 m) is already equipped with a set of risk mitigation measures such as smoke extraction, fresh air supply, short and effective emergency routes and a fixed fire-fighting (FFF) system and therefore possesses an actual high safety level. This, however, does not hold for locations inside the tunnel tubes aside the station. Standard safety systems, which support the self-rescue procedure in case of an incident, are largely missing. Therefore, incidents happening in this ~3,200 m long area, can be complicated to handle without continuous escape walkways, emergency lighting and exits at short distances. To estimate the possible consequences on passengers experiencing one of the 208 hazard scenarios, four different types of physical and physiological consequence models have been set up, namely

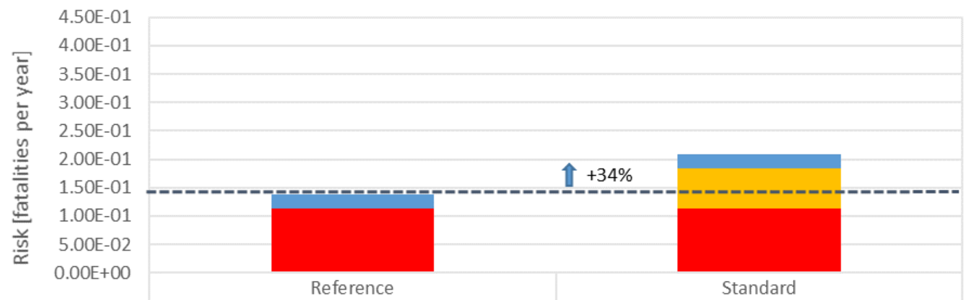
- Consequence model for explosive scenarios,
- Consequence model for toxic gas scenarios,
- Consequence model for fire scenarios as well as
- Consequence model for mechanical scenarios.

Two different incident locations have been considered, namely an incident happening in the station and an incident happening outside of the station in the tunnel tubes. Consequence models allow to calculate the severity of the incidents in terms of the hazard distribution (smoke, extreme heat, toxic gas, amplitude of the pressure wave, mechanical impact etc.), compare (Hull, 2010). In performing the evacuation simulation, the two different infrastructural circumstances according to the station and the tunnel tubes are fully taken into account.

This allows to calculate the consequences in terms of injured and dead passengers for each of the 208 scenarios. Combining this number with the respective incident frequency for each scenario, results in the final risk expectation value for the Vračar tunnel (for each design variant).

3. RISK INCREASE DUE TO DG TRAFFIC

As a consequence of the closed freight-train bypass, ordinary freight trains as well as DG trains have to pass the Vračar tunnel on their way through the city of Belgrade. Legal obligations on the other hand, demand that the risk for passengers is not allowed to increase due to significant operational or infrastructural changes (EU, 2016). Therefore the Serbian Railways Infrastructure were challenged to keep the passenger risk at the level corresponding to the traffic situation before the closure. To assess, in a quantitative manner, the impact of DG traffic on passenger safety, risk expectation values according to the actual traffic – with and without DG – have been calculated. The **standard risk value**, which corresponds to the tunnel design before the bypass closure, but with the actual traffic including DG trains, is compared to the **reference risk value**, which corresponds to the same tunnel design and traffic volume but without DG trains. Based on the specification that the level of passengers risk is not allowed to increase (Europe, 2006) and (CENELEC, 1999), the comparison of both values allows to assess the tolerability of the intended operational changes or, if the **reference risk value** is exceeded, shows the need of additional compensating measures.



	Reference	Standard
total risk	1.38E-01	2.09E-01
mechanical risk	2.50E-02	2.48E-02
DG risk	0.00E+00	7.11E-02
fire risk	1.13E-01	1.13E-01

Figure 2: Comparison of design variants, reference vs. standard variant.

Figure 2 depicts the comparison of the two different design variants. The reference variant resembles the favoured safety reference value, while the standard variant results in an 34% increase in risk due to unrestricted permission of DG transports. Therefore, additional measures are necessary to fulfil the legal obligations. As stated above, the central substation "Vukov Spomenik" is already equipped with efficient risk mitigation measures such as a smoke extraction, fresh air supply and a fixed fire-fighting system, and therefore possesses a very high safety level. The application of the presented risk model resulted in a total risk reduction of approximately 30% due to these station-specific measures. The effect of the transversal ventilation system and the fixed fire-fighting system is demonstrated in **Figure 4**, where the resulting smoke distributions at face level according to a 3D-CFD simulation are depicted along the station and along the central area between the two platforms (waiting hall).

However, since the discussed safety equipment has been installed long before the closure of the bypass, their effect cannot be taken into account in the verification of the legal obligation (risk compensation). Therefore additional prevention and mitigation measures concerning the operation as well as the design and equipment along the tunnel (station and tunnel tubes) have to be investigated.

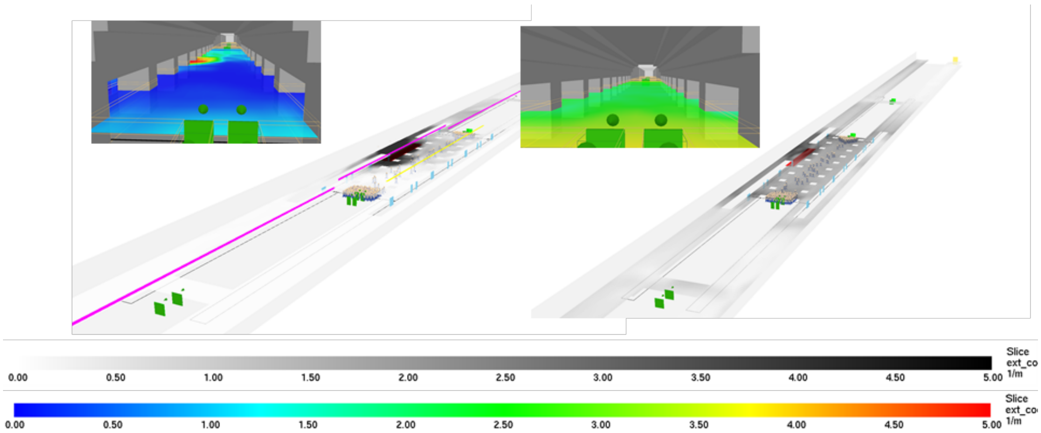


Figure 3: Smoke distribution in the Vukov Spomenik station with (left) and without (right) ventilation- and FFF systems. 300 s after the start of a 30 MW train fire.

4. SAFTY MEASURES

The public transport of line 1 starts daily operating after 4 a.m. and ends before 12 p.m.. Therefore, one obvious operational measure to minimize the risk for passengers is to restrict the DG trains to night hours (12 pm to 4 am) where no public trains are operated and the subway station is closed for passengers (**operational measure I**). On average eight DG trains drive through the tunnel on a daily basis. This number can easily be operated within the permitted time period. Hence, this measure effectively separates passengers from incidents with a potential involvement of DG without the necessity of additional safety equipment and without significant constraints on the operated traffic. The application of the risk model resulted in an expected risk value of approximately 0.14 fatalities per year which already matches the reference risk value. Therefore, operational measure I was assessed to be sufficient to fulfil the legal obligations that the risk for passengers is not allowed to increase due to the allowance of DG traffic through the urban railway tunnel.

To further improve the safety level of the tunnel and decrease the risk for passengers, additional safety measures have been worked out and assessed with the developed risk assessment model. In addition to the restriction of DG trains, passenger trains should not be allowed to stop inside the station, if there is a confirmed incident detection in the opposite tube. As a consequence of this additional operational measure the total number of potentially evacuees in the station is significantly reduced in case of an emergency. This operational measure, already including the restriction of DG trains to night hours, is referred to **operational measure II** and leads to a further risk reduction which can be examined in **Figure 4**.

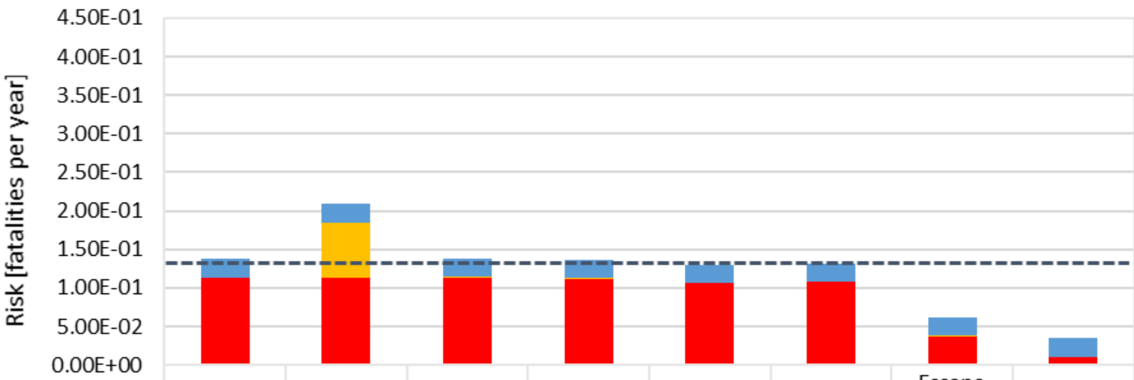
In addition to pure operational measures also benefits from additional infrastructural safety equipment have been analysed. **Guard rails** (GRail) at switches and **hot axle box detections** (HotAB) take effect on the incident rate of train derailments. Guard rails are often installed as punctual measure in areas of higher incident probability (like at switches) and potentially severe consequences (like on a bridge). As the Vračar tunnel accommodates several switches in the area of the southern portal the effectivity of locally installed guard rails was investigated. In contrast, hot axle boxes operate predominately network-wide. To take specific effect on the Vračar tunnel they shall be installed outside the tunnel, at a reasonable distance from the entry portal. Then, a peculiar train with hot wheels or axles can be detected, stopped and checked before entering the tunnel. In general, prevention measures such as guard rails and hot axle boxes are very effective on risk reduction, because they identify hazardous situations and prevent subsequent incidents. However, the major share of the residual tunnel risk - after the mentioned operational measures have already been implemented - arises from passenger train fires, primarily aside the subway stations. Therefore the risk reducing potential due to the avoidance of derailments is small, compared to the overall risk profile. The implementation of guard rails and hot axle boxes leads to expected risk values of approximately 0.13 fatalities per year which corresponds to a further risk reduction of roughly minus 5% compared to operational measure II.

The residual risk in the tunnel is dominated by passenger train fires outside the central station, which is described by the scenario “passenger train on fire can’t manage to reach the station or the portal”. Even this scenario is extremely unlikely, the derived risk potential is relatively high because the possibilities to evacuate a train aside the station are very limited. Common measures to assist during the self-rescue, like a continuous escape walkway, emergency lighting and short distance emergency exits are missing in the tunnel tubes. To analyse the potential for a further risk reduction, two more levels of safety design in the tunnel tubes (aside the station) have been investigated.

Variant one – referred to as **escape way** – corresponds to the implementation of a continuous and well-lighted escape walkway along both tunnel tubes. This will increase the egress frequency of passengers (because of smaller height difference between door and floor level), allow for faster walking speeds along the evacuation path and increase the orientation of evacuees. The application of the risk model results in an expected risk value of 0.06 fatalities per year, which corresponds to a decrease another minus 55% compared to the variant – operational measure II.

In variant two – referred to as **emergency exits** (EE) – cross-passages between the tunnel tubes with emergency exits every $500\,m$ in addition to the lighted escape walkway and the operational measures are considered. Additional emergency exits at 500 m distances will reduce the evacuation time significantly and consequently the duration people are exposed to hazardous substances. The assumption of an emergency exit distance of average $500\,m$ leads to an expected risk value of 0.03 fatalities per year, which corresponds to a total risk reduction of nearly 75% compared to variant operational measure II.

The risk expectation values according to the discussed risk mitigation measures are presented in **Figure 4**.



	Ref.	Standard	Op I	Op II	GRail	HotAB	Escape Way	EE
total risk	1.38E-01	2.09E-01	1.38E-01	1.36E-01	1.30E-01	1.31E-01	6.15E-02	3.44E-02
mechanical risk	2.50E-02	2.48E-02	2.35E-02	2.35E-02	2.32E-02	2.33E-02	2.35E-02	2.35E-02
DG risk	0.00E+00	7.11E-02	8.07E-04	8.07E-04	6.59E-04	7.47E-04	8.07E-04	8.07E-04
fire risk	1.13E-01	1.13E-01	1.13E-01	1.12E-01	1.06E-01	1.07E-01	3.72E-02	1.01E-02

Figure 4: Comparison of design variants.

5. SUMMARY AND CONCLUSIONS

The risk assessment study showed that fire incidents and incidents including DG constitute the major part of the risk profile of the Vračar tunnel. Concerning the incident frequency the analysis results in 1 passenger train fire approximately in a period of 20 years and 1 DG incident circa in a duration of 30 years.

One of the most important conclusions is that in the Vračar Tunnel the passengers risk arising from public transport is more relevant than the risk of freight trains including DG. Nevertheless, operational restrictions for DG transport have to be applied to compensate the additional risks due to adjoined DG-traffic. The temporal separation of DG and public transport (operational measure I) showed to be very effective to reduce these additional risks. This temporal separation, which is already implemented by the operator, as well as the emergency regulation “no stop in station of other trains”, which has to be stated compulsory yet, showed to be sufficient to fulfil the legal obligations to stay below the previous basic risk.

Another essential deduction of the study is that the central station “Vukov Spomenik” is already well-equipped concerning the general tunnel safety. The efficiency of the installed ventilation system and fixed firefighting system were checked in-depth by application of 3D-CFD airflow simulations, which were evaluated by additional airflow measurements for normal operation and also emergency modes. The risk model constituted a risk reduction about 30% for evacuation scenarios in the central station.

As final conclusion of the risk study can be stated that the residual risk in the Vračar Tunnel arises mainly from the scenario “passenger train fire with an unintentionally halt in the tunnel tubes”. Most effective measures to prevent this scenario are related to the used rolling stock. Fire protection measures (construction and vehicle design) should prevent the outbreak and spread of fire and on-board detectors (heat, smoke, flame, etc.) could keep detected trains from entering the tunnel. Referred to rolling stock a substantial need to catch up has been indicated because most of the currently used public trains have seen better days.

On the infrastructure side, mitigation measures for an improvement of poor evacuation conditions along the tunnel tubes could further reduce the residual fire risk. An even, illuminated escape walkway improves the evacuation conditions significantly. Passengers can exit the train faster and evacuate much quicker as compared to running along the ballasted track.

Furthermore, an emergency lightning combined with an escape signage will lead to a more balanced distribution of passenger flows.

Based on the results of the risk analysis the decision to run DG trains through the Vračar tunnel at night hours can be verified as admissible. In general, a detour of DG carriages off the dense inhabited surface areas towards underground structures can be a feasible approach to deal with DG transport risks in cities. This consideration should especially be given for tunnels with a relatively large overburden and a quite low level of development in environment of the portals.

6. REFERENCES

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