TRUCK PLATOONING – A QUANTITATIVE ASSESSMENT OF THE POTENTIAL CONSEQUENCES ON TUNNEL SAFETY

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ABSTRACT

The comprehensive application of the truck-platooning technology promises a multitude of advantages. In a truck platoon, large vehicles drive in a convoy at short spatial distances, taking advantage of reduced air resistance in the slipstream. However, the effects of truck-platooning on user safety in road tunnels have not been fully understood in a quantitative manner. On the one hand, collision frequencies involving large vehicles are expected to decrease due to the necessary improvement of driver assistance systems. On the other hand, the occurrence of truck platoons will lead to higher potential fire loads in case of a truck fire inside a tunnel. Both effects have been taken into account in a quantitative manner in the context of the Austrian tunnel risk model. A reduced collision probability for large vehicles has been estimated based on the analysis of actual driving- and accident data. An increase in the potential fire load and thus in fire risk has been analysed by means of adapted heat-release-rate curves in the fire-consequence model. The influence of a decreased collision probability has been found to be predominant in terms of the overall risk. Therefore the implementation of truck-platooning in in road tunnels can be assessed as slightly beneficial in terms of tunnel user safety.

Keywords: truck platooning, tunnel safety, automotive driving, risk model,

1. INTRODUCTION

Generally speaking, in a truck platoon a variable number of large vehicles are driving in a convoy at short spatial distances of about $10\,m$ to $15\,m$, linked via wireless transmission technology. Only the leading vehicle (LV) is actively controlled by a driver. The following vehicles (FV) are driven by automotive systems, only supervised by otherwise non-active drivers, following the leading vehicle at a constant distance. This concept for the handling of large-vehicle traffic entails several advantages for road users (i.e. transport companies) and road infrastructure operators alike. Due to the short driving distances the air resistance is reduced for all vehicles in the convoy. Thus, less fuel is consumed and greenhouse gas emissions are significantly reduced (Davila & Nombela, 2011). Additionally, the concept of compact large-vehicle convoys increase the traffic capacity of the existing road network.

To enable driving distances below the average reaction pathway, advanced automotive driving systems are mandatory. Consequently large-vehicle collisions arising from human driving errors will potentially be reduced. Technical details of the necessary automotive systems are not discussed in the present paper but the general requirements are assumed to include at least:

- Automatic adjustment of driving speed to maintain a safe distance from the vehicle ahead – Adaptive Cruise Control (ACC)
- Automatic centering on the driving lane which is chosen by the driver of the leading vehicle – Lane Centering Assistant (LCA)
- Automatic vehicle to vehicle communication to instantaneously transmit driving actions of the leading vehicle (V2V-communication)

Compared to the common classification of autonomous driving, the level of automation is reduced to simple tasks for the following vehicles (i.e. maintaining driving distances and lane centering) whereas complex driving decisions are still left to the driver of the leading vehicle. This simplifies the technical implementation of the automotive concept significantly and increases the likelihood and pace of realization.

Given the fast development in terms of technical feasibility, safety related considerations are necessary in parallel to ensure a fluent implementation of this beneficial technology. One specific aspect in this context is the influence of truck-platoons on structural safety and user safety in road tunnels. On the one hand, frequencies for collisions involving large vehicles are expected to decrease due to the necessary improvement of driver assistance systems. On the other hand, the occurrence of truck platoons will lead to higher potential fire loads in case of a truck fire inside a tunnel, because of the increased probability of large-vehicle sequences. In addition to fire consequences also mechanical consequences can potentially increase due to the higher amount of involved mass in case of a collision involving a truck-platoon. The present study focus on the quantitative assessment of the these effects.

2. INFLUENCE OF TRUCK PLATOONS ON THE COLLISION RISK

A significant amount of collisions in every day traffic can be related to human driving errors, either due to intentional, or at least negligent dangerous behaviour, or due to unawareness of the driver. In both cases the spatial distance to the neighbouring vehicles is a key factor when it comes to rear-end collision, or collisions during lane changes. The spatial distance can be chosen too small for the current driving speed or the planed driving manoeuvre, which corresponds to dangerous behaviour, or the drivers focus of attention lies on something else, which results in a delayed reaction time, larger than the net time gap between both vehicles.

2.1. Analyses of the current distance behaviour of large vehicles in road tunnels

To understand of the current driving behaviour of large-vehicle drivers in tunnels along the Austrian motorway, single-vehicle traffic data has been analysed for a representative unidirectional tunnel on the Austrian motorway. The considered tunnel is $7\ km$ long, has 2 driving lanes in each tube/direction, an AADT of $12'300$ vehicles per day in each direction and a share of large vehicles of about 12%. Around $280'000$ single vehicle datasets had been recorded in one driving direction over a continuous period of three weeks. The single vehicle data included the timestamp, the driving lane, the type and length of the vehicle, the velocity of the vehicle and the distance (net time gap) to the vehicle in front (on the same lane).

Two aspects are of specific interest in the context of truck platooning. First, how many large vehicles already drive in a platoon-like configuration (large vehicle following a large vehicle), and second, what are the typical driving distances in such situations. It was found that the share of large vehicles that follow another large vehicle depends on the share of large vehicles on the overall traffic. Obviously because the pure probability of an arbitrary vehicle in front of any large vehicle to be another large vehicle, is proportional to the share of large vehicles on the overall traffic. However**, the average share of large vehicles driving in a platoon configuration was found to be approximately 16% in the considered representative tunnel.**

To analyse the distance between large vehicles driving in a platoon configuration, histograms with respect to the net time gap have been constructed. Figure 1 shows the histogram based on all single-vehicle data points of large vehicles that drive in a platoon configuration. In principle, the driving behaviour strongly depends on the traffic situation in the tunnel (i.e. overall traffic density and share of large vehicles), but no such dependency was found for the net-time-gap distribution. **The average net time gap was found to be $\mathbf{2.4\ s}$** which is equivalent to the minimum spacing between large vehicles according to Austrian law (a minimum of $50\ m$ at a driving speed of $80\frac{km}{h}$). Thus, a significant part of large vehicles driving in a platoon configuration (60% in the considered tunnel) can be assumed to drive at too short distances. The driver assistance systems (CACC), mandatory for the implementation of truck platooning, will therefore lead to a decreasing probability of rear-end collisions due to too short driving distances of large vehicles.

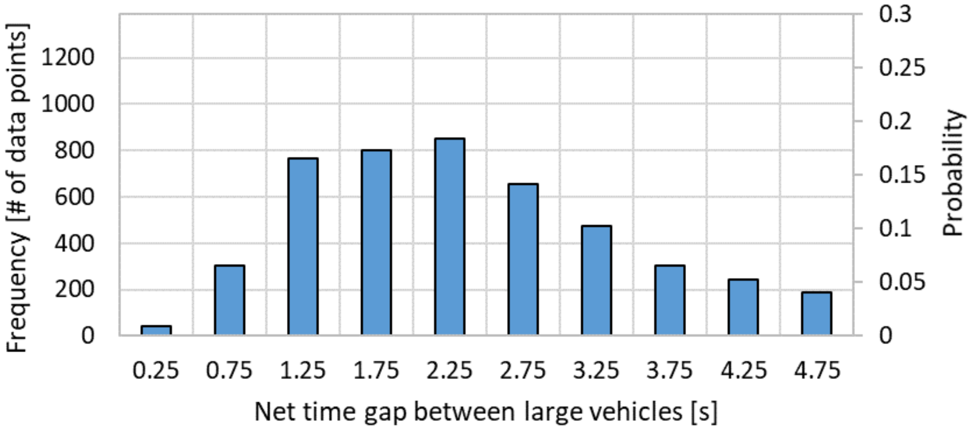


Figure 1: Net time gaps between large vehicles driving in platoon configuration.

2.2. Collision statistics

To quantify the potential reduction of the collision probability due to the implementation of truck platooning, historical tunnel incidents between the years 2007 and 2014, recorded in tunnels on the Austrian motorway network, have been studied. Figure 2 depicts the number of collisions with involvement of large vehicles and their distribution on different incident causes. The statistics is based on an evaluation of incident data from the ASFINAG tunnel accident data base (Canazei & Senekowitsch, 2016).

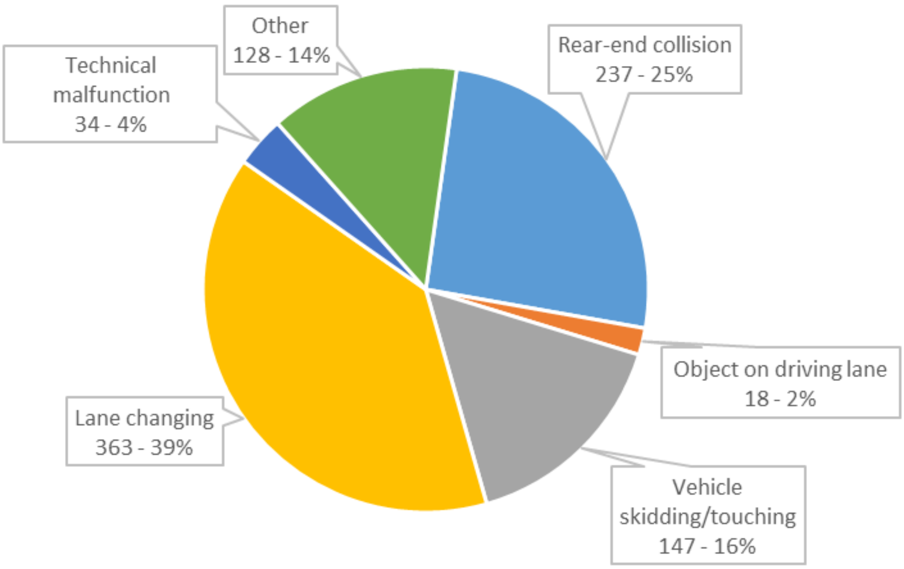


Figure 2: Distribution of recorded collisions involving large vehicles in Austrian tunnels during the time period of 2007-2014.

Table 1: Number of collisions by collision type and collision-causing vehicle for all collisions with involvement of large vehicles

Type of collision	Collisions caused by large vehicle	Collisions caused by other vehicle	N/A
Rear-end collision	**86**	62	89
Collision after skidding/touching	**96**	32	19
Collision due to lane change	**242**	88	33

The majority of collisions with involvement of large vehicles are related to rear-end collisions, lane changes and vehicle skidding/touching, which can be avoided to a great extent by the use of CACC systems. The distribution on vehicle types that caused the respective collisions are given in Table 1. Theoretically, it can be assumed that all rear-end collisions caused by large vehicles can be avoided if the vehicle is part of a truck-platoon and hence equipped with adaptive cruise control systems. Furthermore, collisions due to lane changes as well as vehicle skidding/touching can be avoided, if the causing vehicle is a following vehicle of a truck platoon, since following vehicles are not able to change lanes autonomously. Moreover, lane centring assistance systems and adaptive cruise control systems will avoid according accident types due to human errors. As a result the collision rate of large vehicles in a truck platoon can be assumed to reduce by a factor of

$$f_{Platoon} = f_{rear-end} + \frac{\#_{vehicles}}{\#_{following\ vehicles}}\left(f_{lane\ change} + f_{skidding/touching}\right),$$

Equation 1: Reduction factor for the collision probability of large vehicles in a truck platoon.

where $f_{rear-end}$, $f_{lane\ change}$ and $f_{skidding/touching}$ denote the share of collisions of the respective type which are caused exclusively by large vehicles (bold number in Table 1), on all 927 collisions. If a standard platoon is assumed to consist of one leading vehicle and two following vehicles, the modified collision rate of large vehicles, $\tilde{r}_{large\ vehicle}$, with respect to the share of large vehicles driving in a platoon formation, $S_{Platoon}$, can be calculated according to Equation 2.

$$\tilde{r}_{large\ vehicle} = r_{large\ vehicle} \times (1 - S_{Platoon} \times 0.42)$$

Equation 2: Modified collision rate for large vehicles

Therefore, depending on the portion of large vehicles driving in a platoon formation, **a significant reduction of large vehicle collisions due to the mandatory equipment with driving assistance systems can be expected.**

An additional aspect is the potential increase of mechanical consequences. In case a member vehicle of a truck platoon is involved in a collision, the involvement of additional platoon vehicles cannot be excluded, i.e. if the initially involved vehicle is the leading one. Therefore a potential increase in mechanical consequences is possible. **Even though an involvement of additional platoon vehicles seems very unlikely, the theoretical upper boundary for the increase in mechanical consequences is given by the increase in collision mass.** If a platoon size of three vehicles is considered, this corresponds to a tripling of mechanical consequences.

3. INFLUENCE ON FIRE RISK

Large vehicle fires represent a significant contribution to the overall fire risk in road tunnels. While passenger car fires are restricted to heat release rates of several MW, large vehicle fires can lead to much larger heat release rates of more than $100\ MW$. The presence of truck platoons will not increase the probability for a large-vehicle fire directly, since the number of large vehicles is not assumed to increase by implementation of truck-platooning. Additionally, the probability of a fire spreading to an adjacent vehicle will not be influenced directly, because vehicles will anyhow stop very close to each other in case of an incident, independent of their former driving distance. However, the probability of large vehicles stopping in line will increase. Therefore, in case of a fire spread, also the probability for the involvement of more than one large vehicle will increase.

3.1. Model fire curves

In the Austrian tunnel risk model (FSV, 2015) fire risk is assessed by means of a distinct fire consequence model, which is based on the combination of CFD simulations and an accumulation based survivability- and intoxication model (Purser, 2002). Large vehicle fires are represented by a spectrum of fire curves with maximum heat release rates of 5 MW (driver cabin), 30 MW and 100 MW. Cabin fires (5 MW) are assumed to be too small to spread to an adjacent vehicle and therefore the respective consequences are assumed to be not affected by the presence of truck platoons. Likewise, very large fires with heat release rates of 100 MW are assumed to already represent multiple vehicle fires. Therefore, also 100 MW model fires are not altered. The remaining 30 MW model fire is a typical fully grown large-vehicle fire which potentially spreads to adjacent vehicles.

To estimate the effect of truck platooning on the fire risk, the 30 MW model-fire curve was substituted by a 50 MW fire curve following the same time development as the standard curve, see Figure 3. The modified fire curve represents a fire scenario in which a fire starts on a single vehicle within the platoon and grows according to the standard fire curve of the consequence model. When the fire is fully developed, it spreads on a second adjacent truck which follows again the time development of the single truck fire.

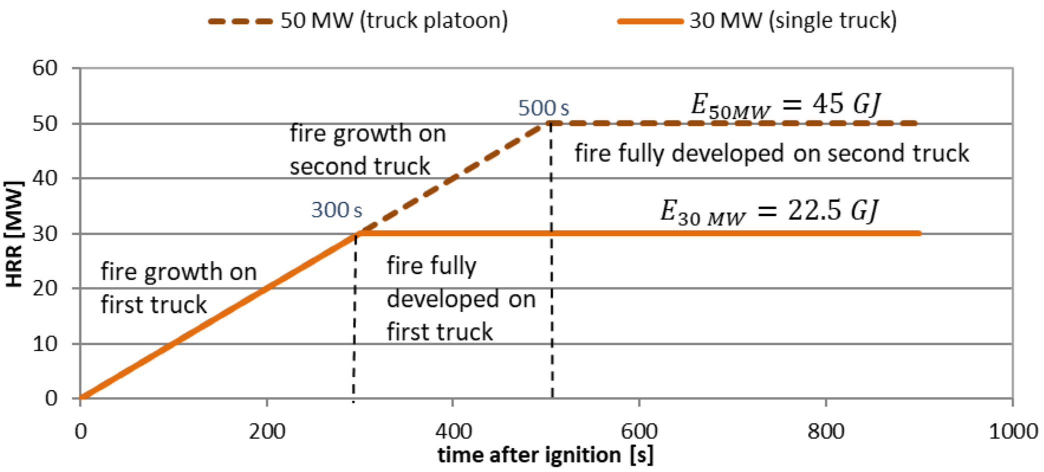


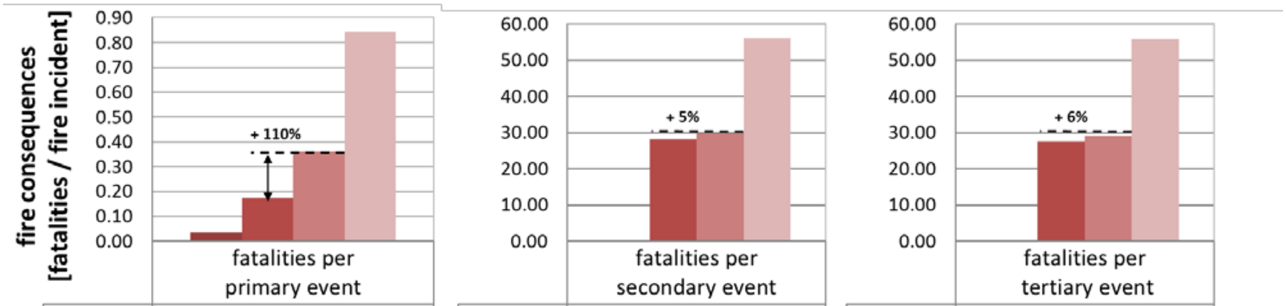
Figure 3: Model fire curves for large vehicle fires, standard 30 MW and adapted 50 MW

3.2. Fire consequence analysis

The Austrian tunnel risk model was applied on a notional unidirectional model tunnel with a standard vaulted two-lane cross-section and a length of 3 km. Parameters of the model tunnel are collected in Table 2. For details on the Austrian tunnel risk model readers are referred to, (Kohl, Forster, & Wiesholzer, 2014), (Frey, Brandt, Heger, & Kohl, 2019). Figure 4 depicts the resulting fire-risk expectation values according to different event types, for 5 MW, 30 MW, 50 MW and 100 MW fires, respectively. The comparison of 30 MW and 50 MW fire risks allows to estimate the potential impact of truck platoons. **For primary events, in which a breakdown or a collision with a consecutive fire occurs during otherwise fluent traffic, the**

fire risk is significantly increased from 0.17 to 0.36 expected fire fatalities per year, which corresponds to an increase of approximately 110%. In case of a primary event, vehicles behind the incident location will queue up, while vehicles in front of the incident car will not be affected and will exit the tunnel without interruption. Therefore only passengers upstream of the fire will potentially be exposed to smoke. However, due to the latency of the detection- and ventilation system (in the magnitude of minutes), back-layering will occur in the initial fire period and expose passengers upstream of the fire to smoke, in particular for tunnels with negative inclinations. The increased maximum heat release rate, due to the fire spread on an adjacent large vehicle, leads to an increased back-layering and therefore to a higher fire risk for primary large-vehicle events.

Secondary (follow-up collision + consecutive fire) and tertiary events (fire during traffic congestion) represent fire incidents during already congested traffic, either due to a preceding traffic incident or due to traffic overload. In such cases the fire risk is dominated by persons downstream of the fire which are heavily exposed to smoke as a result of the initial as well as the forced longitudinal airflow. The overall fire-consequences are much higher in such events and back-layering plays a minor role. **Therefore, a similar absolute increase between 30 MW and 50 MW fires leads to a small relative increase, in relation to the initial fire consequences of secondary and tertiary events (fires during congested traffic).**



	fatalities per primary event	fatalities per secondary event	fatalities per tertiary event
5MW	0.03	0.19	0.19
30MW	0.17	28.25	27.54
50MW	0.36	29.76	29.20
100MW	0.84	56.16	55.82

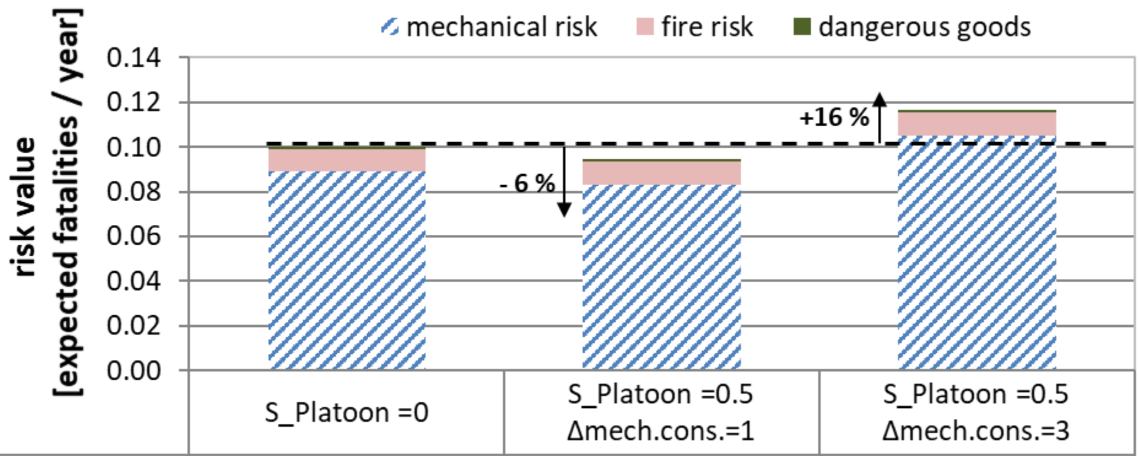
Figure 4: Fire consequence number for primary, secondary and tertiary event according to the Austrian tunnel risk model.

Table 2: Model tunnel – relevant parameters.

Tunnel parameter	Parameter value
Tunnel system	Unidirectional tunnel with 2 lanes
Tunnel length	3’000 m
Emergency exits	9 (every 300 m)
Gradient	-1.5%
Tunnel cross-section	Vaulted, 46.6 m^2
Average traffic volume	30’000 vehicles per day in each direction
Ventilation system	Longitudinal ventilation 13 jet fans, thrust = 835 $\pm$ 10% N, diameter = 1.0 m

4. RISK ASSESSMENT

To discuss the impact of truck platooning on passenger risk in tunnels in a holistic manner, the decrease in collision probability as well as the increase in fire consequences have been implemented in the detailed version of the Austrian tunnel risk model. The results, without truck platooning and with 50% of all large vehicles driving in a truck platoon, are depicted in Figure 5. For a truck-platooning share of 50%, two variants for the increase of mechanical consequences were applied. For variant 1 no increase of mechanical consequences in case of a truck-platoon collision was considered. This corresponds to the minimum effect possible. Variant 2 corresponds to the maximum increase in mechanical consequences, i.e. a tripling (for an assumed platoon size of three vehicles). If no increase in mechanical consequences is assumed, the decrease in collision probability, due to 50% truck-platooning, dominates over the increase in fire consequences. The assessment results in an overall reduction of the expected risk value of approximately 6%. On the other hand, the expected risk value increases by 16%, if the maximum increase in mechanical consequences is assumed. Both extreme-variants can be interpreted as boundary values that enclose the result for a realistic, but yet unknown increase of collision consequences due to truck platoons. However, due the driving assistance systems, i.e. adaptive cruise control and vehicle-to-vehicle communication, the velocity of the following vehicles will immediately be reduced in case of an unforeseen event, which potentially ends in a collision. Consequently, the involvement of additional large vehicles will either be avoided completely (variant 1) or the impact of the consecutive vehicles will happen at a reduced velocity. Therefore, the exact result will be much closer to the case with a reduced overall risk value.



	S_Platoon =0	S_Platoon =0.5 Δmech.cons.=1	S_Platoon =0.5 Δmech.cons.=3
dangerous goods	0.001	0.001	0.001
fire risk	0.010	0.010	0.011
mechanical risk	0.089	0.083	0.105

Figure 5: Risk expectation values with respect to the share of large vehicles driving in truck platoons.

5. SUMMARY AND CONCLUSIONS

The analysis of actual large-vehicle traffic data indicates that current driving distances between large vehicles are significantly shorter than legally required. This is also reflected in the high amount of large-vehicle rear-end collisions reported in tunnels on the Austrian motorway network. An analysis of collisions and in particular accident causes showed that up to 40 % of all large-vehicle collisions could be avoided as a consequence of driving assistance systems, which are mandatory for vehicles driving in a truck platoon. On the other hand, an increase in the likelihood of large-vehicle sequences may also increase the probability of fires with very large heat release rates, if the fire spreads from one large vehicle to an adjacent large vehicle. However, the application of the Austrian tunnel risk model on a notional model tunnel, including detailed CFD- and evacuation simulations for increased heat release rates, showed that the decrease in collision probability slightly exceeds the impact of an increased fire load.

In principle also an increase in mechanical consequences must be considered, in case of a collision where more than one large vehicle of the platoon is involved. But this increase can be assumed as negligible, for two reasons. First, the mandatory driving assistance systems will either avoid an involvement of additional vehicles or at least reduce the impact velocity significantly, due to instantaneous breaking. Therefore only very specific sequences of events, where the stopping distance of the vehicle involved in the initial collision is significantly reduced, can lead to an involvement of additional platoon-vehicles, and further, to an increase in collision energy. Second, from a statistical point of view, the major part of collision consequences, i.e. personal damage, arises from passenger cars, which contain more persons and are exposed to severer damage. Due to the smaller mass and lower centre of gravity, the consequences for the passenger car can be expected to be very close to the maximum. Therefore an impact of additional vehicles cannot lead to a multiplication of consequences.

Truck platooning is discussed as a promising concept to increase efficiency of large-vehicle traffic while fuel consumption and emission of greenhouse gases are reduced. The quantitative risk assessment showed, with respect to the accuracy of the applied model, that no major impact on the safety of tunnel users has to be expected. Consequently no restrictions on truck platooning have to be deduced based on tunnel-safety considerations. However, similar assessments are also necessary, with respect to other parts of road infrastructure, like bridges or access lanes, to generate a holistic concept for the safe and efficient implementation of this new technology.

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