Pre-print

How truck-platooning changes the extreme values of load-effects in single-span bridges.

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Abstract

The load model defined in EN 1991-2 is derived from traffic measurements taken in Auxerre (FR) in 1986. Since then the vehicle industries have changed a lot. For different future traffic scenarios, changes in load patters are expected. Automated driving, especially truck platooning, will have an impact on future bridge loads. Due to synchronization of traffic flows, or reduced distances between trucks- as it is used for truck platooning- increase of the traffic load per road meter follows. Within this paper, a large-scale parameter study of different bridge types loaded with randomised traffic flows and platoon scenarios is investigated. Structural safety is evaluated for concentrated vertical forces with dynamic resonance interaction on bridges with respect to randomized traffic. Key parameters such as critical intervehicle distances or dynamic load amplification were identified and discussed.

Keywords: Load models, bridge dynamics, future traffic loads, platooning, extreme value, exceedance probability.

1 Introduction

Connected and automated transport systems (CATS) are expected to be introduced in increasing numbers over the next decade. Truck-platooning is a possible future technique for the heavy vehicle traffic. The vehicle industry has already tested the functionality of truck platooning where different trucks are coupled together by an "electronic" drawbar (Figure 1). In addition to the economical and logistical advantages of automated driving, shortage of truck drivers and positive environmental aspects such as saving fuel by using the positive wind shadow-effects of a fleet are main drivers for this technology.

Truck platooning represents a change in the traffic composition, which has potential impacts on the bridge capacity to carry these possible future loads. Due to synchronization of traffic flows or reduced inter vehicle distances - as it is used for platooning to use the advantage from slipstream- the loading on infrastructure and bridges will increase.

Figure 1. Illustrated truck platoons which is developed in the vehicle industries, Photo ©Scania- published Feb 27, 2020.

Following main effects were identified as relevant for bridges and analyzed in this study:

- Static traffic load effects: the reduced vehicle distances in a platoon cause an increase of traffic load per road meter. Therefore, a potential increase of maximum traffic loads during bridge's lifetime can be expected.

- Dynamic amplification: the dynamic interaction between the vehicles, road surface and the bridge leads to an increase of the traffic loading. The repetitive composition of trucks in a platoon can potentially increase the dynamic amplification mostly due to resonance, if the interaction with bridge eigenfrequency turns out to be unfavorable.

Further, platoons are also expected to have an impact on the braking forces acting on the bridge. This effect was investigated in [1], but is not in scope of this paper.

The focus of this paper is to evaluate the impact of truck platoons on urban highway bridges which should show the possible effects of concentrated vertical forces and synchronized effects causing dynamic resonance interaction on bridges. The study is based on a large-scale parameter computation of different bridge types and randomized traffic flow conditions within the scope of the H2020 -project Levitate [1].

2 Background Information

2.1 General normative background

The model for traffic loads on bridges is standardized and defined in the EN-1991-2 document (Eurocode 1) [2]. It is representing the effects of vehicle loading and is mainly used in the design of new bridges and with modifications in the assessment of the load bearing capacity of existing bridges, which are defined individually for each country through national adjustment factors – usually for different classes of routes. This traffic load model was derived based on axle-load measurements performed near Auxerre, France [3][4] in 1986 and includes statistical assumptions for the future traffic volumes. The Eurocode 1 contains 4 different types of load models on road bridges. Most relevant is load model 1 (LM1), which is used for general and local verifications and was calibrated for loaded bridge spans of up to 200 m. Load models LM 2, 3 &4 cover the effects on short structural members, load of special vehicles and crowd loading of pedestrians. This work analyses the global ultimate limit states ULS (longitudinal bending moment and shear), which are covered primarily by the load model LM1. Adjustment factors α_{Qi}, α_{qi}, α_r are defined in national annexes to account for traffic compositions that differ from the basis traffic measurements used for deriving LM1.

2.2 Vertical traffic load effects on bridges

The traffic flow exerts different forces on the bridge, which must be transferred by the bridge structure into the subgrade. Usually, the engineers divide the traffic forces on road bridges into vertical (weight of vehicles) and horizontal (braking, acceleration, centrifugal force) forces, which are also so defined in the different standardisations like EN 1991-2 [2]. Vertical forces dominate the action effects. They can be split into their quasi-static and their dynamic part. The quasi-static part represents the bridge-vehicle interaction without any inertia effects and is in principle equivalent to traffic load effects in case of an extremely slow travel speed v ($v \rightarrow 0$). The dynamic part represents additional effects that arise from inertia and resonance effects of the interacting system bridge-vehicle, additionally influenced by road irregularities (impulse effects), at actual travel speed. When using the Eurocode load models, all these aspects are already included in the standardised model. For the structural design, additional safety factors are taken into account on the load side. The most common way is to use partial safety factors as part of a semi-probabilistic safety concept in order to fulfil the structural safety about the probability of occurrence of different loads.

Quasi-static traffic load effects on bridges are usually evaluated using influence lines / influence areas. The influence line is a function of axle load position on the bridge and describes the value of an internal bridge forces (e.g. the bending moment or shear force in a girder at point of interest) that would be produced by a unit axle force at different positions on the bridge. The total traffic-induced quasi-static cross-section force is then calculated as sum of influence line values at axle load positions multiplied by the axle forces.

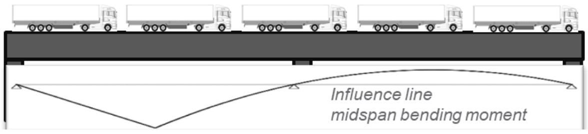

Figure 2. Influence line midspan bending moment of a two-span bridge.

Calculation of maximum expected bridge load effects can be performed using synthesis of the time-history of traffic-induced cross-section forces (Figure 3). To evaluate the expected maximum load effect during bridge's lifetime, it is necessary to evaluate the cross-section force maxima in many equally-long time periods and construct an extreme value distribution (Figure 4). The expected maximum must be defined in a probabilistic way as the value, which has a specified exceedance probability within bridge's lifetime. For the LM1 model, the exceedance probability was set at 5 % in 50 years.

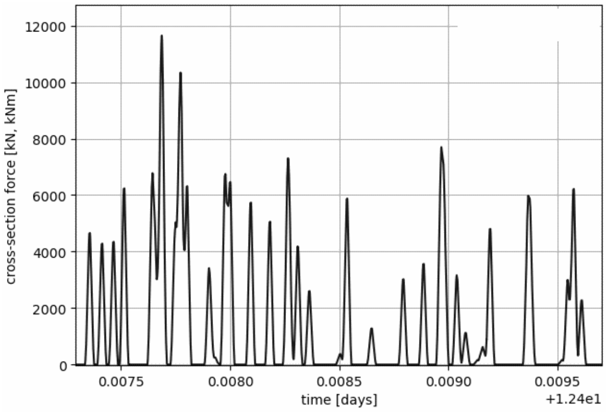

Figure 3. Example of time-history of bridge cross-section force.

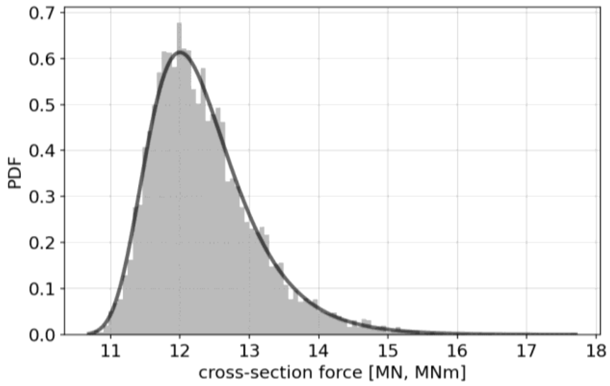

Figure 4. Example of histogram of weekly maxima with fitted extreme-value distribution.

The dynamic effect of traffic load actions increases the quasi-static cross-section forces. This increase, which is caused by traffic-induced vibrations (dynamic loads with bridge resonance and inertial effects) of the bridge, must be added to the quasi-static effects; this is particularly relevant for railway bridges. Figure 5 shows an example of quasi-static bridge response and the response including dynamic effects. In this example, the maximum dynamic force is increased by 7% when compared to the quasi-static maximum.

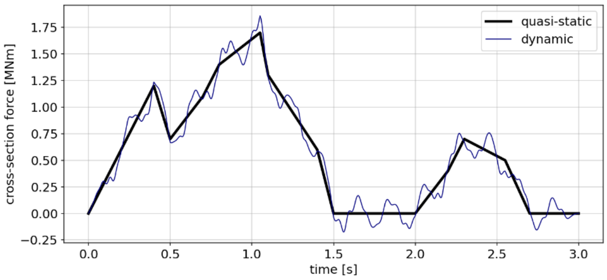

Figure 5. Example of comparison of quasi-static and dynamic history of the cross-section force.

As already mentioned, the load models of the Eurocode already include the dynamic effects. In simulation using real traffic loads, these effects must be additionally considered.

3 Traffic simulations

Basis for the large-scale parameter computation are randomized traffic flow conditions, which were applied on different bridge types to determine the expected maximum internal cross-section forces. This approach was used here to compare the expected maxima of bridge loading in different traffic scenarios, including generic future loads of truck platoons based on different assumptions. In here, it is necessary to carry out traffic simulations of many years to sufficiently represent extreme value distributions of the occurrence probabilities of different traffic load conditions.

3.1 Traffic scenarios

The following types of traffic scenarios were analysed:

- **Current heavy traffic:**
  Status quo used as a base scenario.
- **Heavy traffic with truck platoons:**
  Various future platoon compositions mixed into the current traffic.

To generate the traffic for bridge simulations, it is necessary to create vehicle sequences using the given traffic parameters (composition of vehicles, traffic intensity, vehicle distance distribution, vehicle parameters such as axle distances, loads). This is done by generating random samples from given traffic parameter distributions, thus creating a randomized traffic flow that follows the given traffic parameters. Following assumptions were included:

- Traffic flow is a random stationary process; evolution of the traffic flow over time is not considered.
- Vehicle speed v is constant and all vehicles in one lane share the same speed.
- Vehicles do not change lanes while on the bridge.

Most vehicles comply with the prescribed limits of gross vehicle weight. Vehicles that violate the prescribed limit do so in an appropriate manner – the excess weight is not very large. That means, a certain percentage of vehicles with gross weight slightly over 40 tons occurs, but for example a single vehicle with 60 tons does not (except for special vehicles that have the permit- which are not considered within this study).

The distribution of the number of vehicles between the 2 lanes is assumed as 80% (right) and 20% (left) [3][5] for a two-lane urban highway in the case of low traffic intensity.

In addition to flowing traffic, congestion situations need to be considered. The congestion is expected to produce traffic events that are most relevant for evaluation of maximum bridge cross-section forces, since more vehicle mass is concentrated on the bridge during congestions. In here, a simple congestion model was adopted from [5], which is governed by two parameters:

- P_{cong} is the probability that the following vehicle is congested, given that current vehicle is congested.
- P_{flow} is the probability that the following vehicle is not congested, given that current vehicle is not congested.

Generation of congestion states of all vehicles in the right lane according these simple rules provides an estimate of congestion forming. Congestion in the left lane follows the congestion state of the right lane in this model. Vehicle distance d_c in congestion is an important parameter, which governs the concentration of mass on the bridge. Here, very few actual data are available, so three models for vehicle distances were investigated. They are listed in Table 1 and describe distributions used for generating inter-vehicle axle distances in congestion, i.e. the distance from last axle of one vehicle to first axle of the following vehicle. Since the normal distribution is unbounded, additional limits were introduced, limiting the values of $\mathcal{N}(10,5)$ to the range 3 to 20 m.

Table 1. Inter-vehicle axle distances d_c in congestion (adopted with modifications from [5])

Notation	Distribution	μ [m]	σ [m]	min [m]	max [m]
C_5	Constant	5	0	5	5
$\mathcal{U}(5,15)$	Uniform	10	2.89	5	15
$\mathcal{N}(10,5)$	Normal	10	5	3	20

3.2 Normal traffic (without platooning)

For the baseline scenarios, traffic with different properties was simulated, all without platooning. The simulated urban highway had two lanes. A traffic scenario without platoons is characterized by these properties:

- Traffic volume n_v
- Truck composition (Traffic mix)
- Congestion model P_{cong}

The traffic volume is given by the total number of vehicles per day (daily traffic volume). The traffic flow on the bridge is simulated as constant; daily or weekly cycles of traffic intensity are not considered.

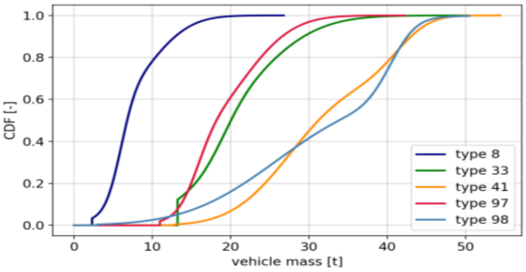

Figure 6. Density functions of weight distributions for different vehicle types.

The truck composition was varied among the scenarios of heavy traffic with different traffic mixes which were identified as relevant in [5] (see Figure 6). In the actual performed investigations "traffic mix A" (Table 2) was defined as very relevant and therefore used as baseline [6].

Table 2. Constitution of different vehicle types T (EuroClass-E13) of a certain "traffic mix A" (adopted with modifications from [5])

Lane	T 8 [%]	T 33 [%]	T 41 [%]	T 97 [%]	T 98 [%]	Car [%]
right	11	5	17	8	59	0
left	2.2	1	3.4	1.6	11.8	80

The congestion model is determined by three parameters: distribution of vehicle distances, P_{flow} and P_{cong}. A variation of congestion parameters was performed here to analyze their influence on traffic load effects, since the choice of their values is often difficult due to lack of data.

3.3 Platooning scenarios

The traffic with platooning is characterized through additional parameters, which describe the platoon properties. The platoon properties in the implemented model are given by following parameters:

- Platooning penetration rate [%] per vehicle type
- Vehicle distances d_μ in a platoon
- Number $\mathcal{U}$ of vehicles in one platoon

The platooning penetration rate for a vehicle type is defined by the percentage of vehicles of that type that form platoons. In here, the platooning penetration rate was varied between 20% and 80% of all heavy vehicles. The number of vehicles in one platoon was generated as random sample from a uniform distribution $\mathcal{U}(3{,}10)$. The distance of vehicles in a platoon d_μ was defined using a normal distribution $\mathcal{N}(0.5,\ 0.1)$ with mean of 0.5 m and standard deviation 0.1 m, limited by the bounds of ±4σ.

Overall, following parameters were varied:

- Traffic volume n_v
  39000 or 69000 vehicles per day
- Distances in congestion
  constant (C_5) or normal distribution $\mathcal{N}(10{,}5)$
- Congestion probabilities
  $P_{cong} = 0.99$ & $P_{flow} = 0.999$ or $P_{cong} = 0.999$ & $P_{flow} = 0.9999$
- Platoon penetration rate (heavy vehicles)
  20%, 40%, 60% or 80%

So, the different combinations of these parameters resulted in 32 traffic scenarios that include platooning and congestions. Additionally, 8 platooning traffic cases without congestions were analyzed. In here, only the traffic volume and platoon penetration rates were varied.

In total, 40 traffic cases with platooning were analyzed.

4 Bridge model

The bridges were modeled as a single beam supported at both ends, with free rotation. The relevant limit states are the midspan bending moment and the shear force at the support(s). The traffic load effects were evaluated using the influence lines. It was assumed that the bridges are designed for the current load model according to EN 1991-2 [2].

Given the bridge models used here (simply-supported beam), the quasi-static traffic load effects were determined using influence lines; they are independent of the bridge construction type. The bridge type influences then only the self-weight of the bridge. All bridges were modelled with a bridge deck width of 10.5 m (incl. edge beams), carrying two lanes. Besides bridge type and span length, the permanent load μ was variated between 20 and 40 t/m for concrete bridges, 10 to 15 t/m for composite bridges and between 6 to 10t/m for steel bridges, depending on the bridge span. More details on the bridges are given in [6].

To evaluate the characteristic load, extreme-value distribution from maxima of many 50-year periods should be used. Since it is not feasible to simulate many 50-year periods, shorter periods were used instead, and the result was converted [6].

To estimate the increase of cross-section forces due to dynamic effects incl. resonance, transient dynamic simulations using moving load models were performed. This was done with selected traffic scenarios/platoons from which the dynamic amplification factor was determined as the ratio to the quasi-static load.

5 Results

The change in traffic composition due to platoons is expected to lead to higher bridge internal forces. In here, a focus was the ultimate limit states (ULS) of midspan bending moment.

To make the results on different bridges comparable, the impacts are not expressed in absolute values of bridge internal forces, but relative to the bridge internal forces caused by Eurocode load model LM1. The forces caused by LM1 load model are deterministic. On the other hand, the simulated traffic is random, and the forces caused by this traffic are evaluated as probabilistic, expressed through an extreme-value distribution.

Therefore, the impact of simulated traffic is evaluated in terms of the probability of exceeding the effects of load model LM1. Since new bridges are designed for the loads of load model LM1, it is assumed that they have the respective load-carrying capacity.

The definition of load model LM1 according to EN 1991-1 [2] presumes that its exceedance probability in 50 years is 5%. Therefore, this probability is regarded as the “code level”. The resulting bridge forces are evaluated in terms of the probability, that they exceed the forces from Eurocode load models: bending moment $M_{Q,k}$.

If the probability that $M_{Q,k}$ will be exceeded within 50 years is above 5% (i.e. $P\left(\max_{50y} M_Q > M_{Q,k}\right) > 0.05$), the structural safety can be regarded as reduced. Higher exceedance probabilities mean lower structural safety.

5.1 Baseline scenarios

Figure 7 shows the results for traffic with different congestions probabilities using traffic mix A (Table 2) with a traffic volume n_v=66000. The congestion probability affected the results; further analyses were done with values of P_{cong}=0.99 or 0.999 and P_{flow} to 0.999 or 0.9999. Figure 8 shows the $M_{Q,k}$ exceedance probabilities for different distances of congested vehicle (Table 1). It is apparent that the congestions become more relevant for bridges with longer spans. The comparison suggests that the assumption of vehicle distances $\mathcal{N}(10{,}5)$ is more conservative for bridges with span lengths up to 80 m for the bending moment ULS. For bridges with span above 80 m, the constant 5 m vehicle distance (C_5) is more conservative.

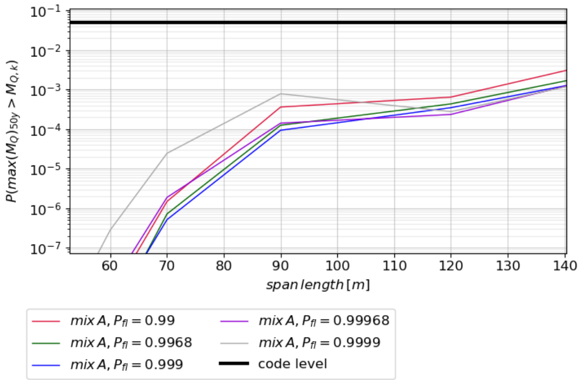

Figure 7. Bending moment exceedance probabilities for different congestion assumptions.

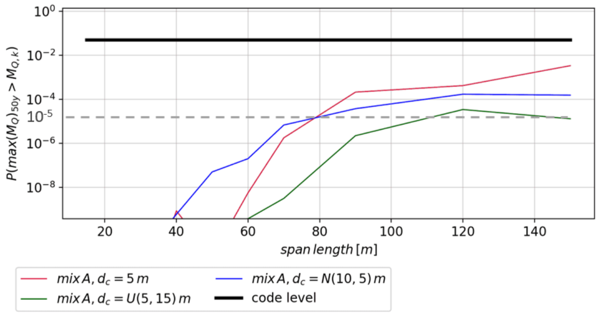

Figure 8. Bending moment exceedance probabilities for traffic mix A with different vehicle distances in congestion and n_v=66000.

5.2 Platooning scenarios

After the platoons were introduced into to the simulated traffic, the bridge internal forces increased significantly in bridges with longer spans. Figure 9 shows the increase of probabilities of exceeding the load effects of LM1 load model. In here, the red curve is the traffic case without platooning (note that the scale of y-axis is changed compared to Fig.8) and n_v=66000 vehicles/day for traffic mix A. For platoons the volume was reduced to n_v=39000 vehicle/day and constant congestion distances (C_5) and P_{cong}=0.99, P_{flow}=0.999 were chosen. The four curves are representing results with 20%, 40%, 60% and 80% platooning penetration rate (related to the total heavy vehicle traffic).

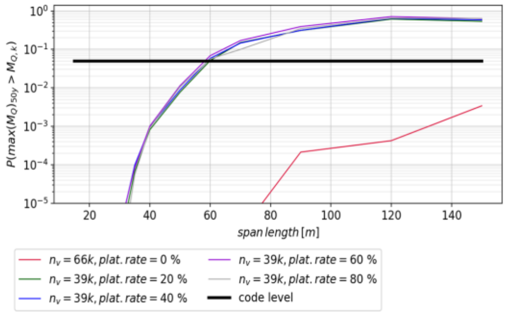

Figure 9. Bending moment exceedance probabilities in different platooning penetration rates (incl. congestions); intervehicle distances in the platoon d_μ= 0.5 m (σ=0.1 m).

In normal traffic, a sequence of vehicles with randomly distributed distances is assumed. Truck platooning represents a new, different scenario. It can be observed that the platooning penetration rate does not have significant effect on the exceedance probabilities. Even a low penetration rate of 20% produced already a large increase of cross-section force extremes, even if the traffic amount was less than in the baseline. To evaluate the influence of inter-vehicle distances, the bridge response simulations were repeated for different values of inter-vehicle distances d_μ within the platoons between d_μ = 0.5 and 10 m.

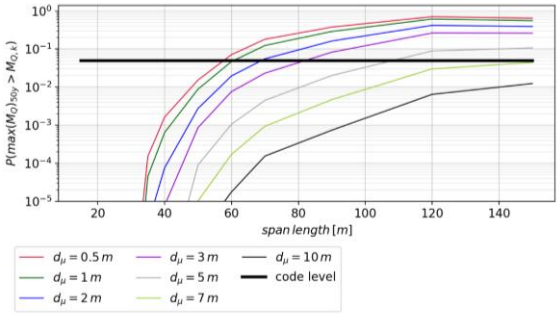

Figure 10. Bending moment exceedance probabilities for traffic mix A, traffic volume of 39000 vehicles/day, platooning penetration rate 60%, congestion distances $\mathcal{N}(10{,}5)$, P_{cong}=0.99, and different inter-vehicle distances d_μ within platoons.

Figure 10 shows the results of exceedance probabilities for the bending moment ULS. The change of inter-vehicle distances has a significant effect on the exceedance of the characteristic load effects $M_{Q,k}$.

5.3 Dynamic amplification

The bridge-vehicle/platoon interaction was investigated using transient dynamic analysis. Resonance effects at different configurations were identified, as seen in the example in Figure 11, using different vehicle types at a speed of 80 km/h. As known for railway bridges, the interaction can cause resonance effects at certain vehicle speeds, when axle distances meet the natural frequencies of the bridge.

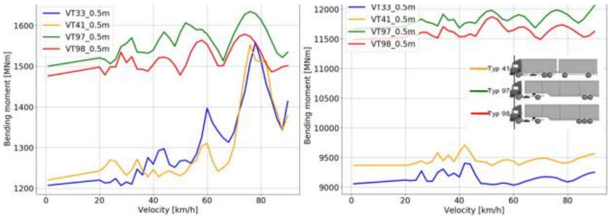

Figure 11. Dynamic analysis of traffic events with platoons. Concrete bridge L=20 m (left), and steel bridge L=60 m (right).

Figure 11 is an example of 2 bridges loaded with platoons of different vehicle types. The concrete bridge had a dynamic load amplification factor of max. 25 % for the vehicle type T33 and T41. The longer steel bridge (Figure 11 right) had very low dynamic amplifications.

6 Conclusions

This paper shows the impact of possible future truck platoons on urban highway bridges. A large-scale parameter study of different probabilistic traffic flows with and without truck platooning was investigated.

Truck platooning represents a change in the traffic composition, which has potential impacts on the bridge capacity to carry these new loads. For the baseline traffic simulation – which is mostly based on literature approaches – different models for vehicle distances in combination with congestions models were investigated. The calculated internal forces (bending moments) were benchmarked with the code-level, which presumes that its exceedance probability in 50 years is 5%.

It could be shown that the congestion models have a major impact on traffic loads and the bridge loading, especially for longer bridges. The comparison of different vehicle distances in congestion suggests that the assumption of vehicle distances $\mathcal{N}(10,5)$ is more conservative for bridges with span lengths up to 80 m for the bending moment ULS. For bridges with span above 80 m, the constant 5 m vehicle distance (C_5) is more conservative.

But a far larger impact on bridge load extremes is expected when the traffic gets synchronized. Platooning with a platoon rate of only 20% (related to heavy traffic) strongly increases bridge loading, and it does not change very much if the penetration rate increases. The biggest influence on the vertical load has proven to be the distance between the vehicles within the truck platoons, as already suspected. With the assumptions made, it was shown that platoons with a vehicle spacing of 0.5 m will exceed the vertical loading during the service life with bridge spans of approx. 40 - 50 m. The intervehicle distance could be a controlling parameter for truck platoons with respect to existing bridges.

Transient dynamic load analysis has demonstrated an increase of up to 25-30% through synchronized loading as an example. Dynamic load amplification needs to be further investigated for different bridge and platoon- configurations. This problem is well known from the dynamics of railway bridges, where the dynamic aggressiveness is evaluated in advance for new train types. Also, research is needed on congestion models and vehicle distances in congestion.

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