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ON THE EFFECTS OF MODIFIED LANE CONFIGURATION DUE TO CONSTRUCTION WORKS ON BRIDGE LOADING

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Abstract. Construction works are frequently recurring events within highway networks, temporarily altering the characteristics of the traffic flow and hence of the bridge loading process. Consequently, highway bridge superstructures usually carrying unidirectional traffic might have to face modified configurations, with possibly altered lane widths and transverse lane positions, or even an increased number of lanes and the occurrence of bidirectional traffic flow. While usually covering only short periods compared to the average service life of a bridge, such scenarios might represent extreme loading situations, potentially dominating the traffic loading process. Therefore, their consideration and accurate modeling in the course of traffic load assessment and development of object-specific traffic load models are of utmost importance. The presented study analyzes data from bridge monitoring along federal highway A92 in Southern Germany. The data covers standard and different modified lane configurations due to construction works. Besides analyzing the effects on traffic flow characteristics and resulting occurrence rates of multiple truck presence on the bridge, the consequences for load effects and their extreme value behavior are also evaluated. The findings support verification of related code background works and can serve as base and guidance for future research efforts on bridge load modeling in this context.

Keywords: Bridge loading, modified lane configuration, monitoring, multiple truck presence, transverse distribution factor.

1. Introduction

Throughout the regular service life of a highway bridge, occasional construction works along the road might lead to a temporary modification of traffic lane configuration on the roadway, with possibly altered number of lanes, lane widths, and transverse lane positions. These modifications potentially cause changes in the characteristics of the traffic flow and the loading of the bridge, i.e. the quantity and position of truck vehicles simultaneously present on the bridge. Therefore, such scenarios might represent extreme loading situations, potentially dominating the bridge loading process.

Consequently, the possibility of modified lane configurations on a bridge needs to be considered for code calibration of traffic load models. In the background works for the German national annex to EN 1991-2 and the reassessment guideline for existing road bridges (*Nachrechnungsrichtlinie*), this scenario is accounted for [1, 2]. A modified lane configuration with bidirectional traffic on four traffic lanes is considered, with a ratio of 20 % of truck vehicles per direction traveling on the respective fast lane, allowing for the occurrence of truck overtaking events for each driving direction. Additional investigations of altered bidirectional four-lane configurations are performed in [3]. Based on a (more realistic) reduced width of the respective fast lane, the assumption is made that truck overtaking is not possible due to spatial constraints. The assumed absence of truck vehicles on the fast lane (no overtaking trucks) reduces the level of bridge loading. Investigations within the scope of mentioned background works are performed based on numerical simulations and for a limited set of bridge structures. The resulting load levels are evaluated based on extrapolated characteristic values with a return period of 1000 years (even though the occurrence period of modified lane configurations is considerably shorter compared to the standard lane configuration). Measurements from an actual structure to compare and verify the effects of modified lane configuration on traffic flow characteristics and bridge loading are unknown to the author.

Within this context, the presented study analyzes monitoring data from a highway bridge along federal highway A92 in Southern Germany. The monitoring data covers - besides standard two-lane configuration - two periods with different modified lane configurations due to constructions works along the considered highway section: a modified unidirectional two-lane configuration and a bidirectional four-lane configuration. Direct measurement of the resulting load effects with strain gauges and additional traffic monitoring with a laser scanner for vehicle detection, counting, and classification are performed. The monitoring data allows for an in-depth comparison of the modified lane configurations with the standard case. Besides analyzing the effects on traffic flow characteristics and resulting occurrence rates of multiple truck presence on the bridge, consequences for load effects and their extreme value behavior are also evaluated. The findings from this study support verification of related code background works and can serve as base and guidance for future research efforts on bridge load modeling accounting for scenarios of modified lane configurations.

2. Methods

2.1. Signal Processing

The raw signal of strain sensors is composed of different parts, mainly differing in their rate of change:

- load effects due to temperature and other non-permanent constraining loads (low rate of change, usually several minutes or longer)
- road traffic (static) load effects (medium rate of change, for structure and sensor locations in this work up to a few seconds)
- dynamic effects due to excitation by passing vehicles and interaction with structure (high rate of change, fractions of second)
- measurement noise (wide range of rates of change, possibly over entire frequency spectrum)

Signal processing is necessary to extract the relevant parts of the raw signal resulting from road traffic, i.e., passing vehicles' (static) load. For this purpose, the procedure from [4, 5] is adopted within the scope of this work, performing signal decomposition exploiting the different rates of change of the single signal components. For this purpose, mean filtering (excluding parts of the signal with a low rate of change) and low pass frequency filtering (excluding dynamic effects and most parts of measurement noise) are applied.

Mean filtering is done based on block-wise determined and linearly interpolated mean values. The choice of block size constitutes a compromise between sufficiently detailed representation of the signal parts with a low rate of change and 'robustness' against the influence of the signal part due to traffic loading on the resulting block mean values. For low pass frequency filtering, a Butterworth filter of seventh order is applied. The cutoff frequency f_{cutoff} is chosen based on the natural frequencies of the monitored structure. As the focus is on analyzing the load effects resulting from the static load of passing vehicles, the value should be sufficiently low to exclude all significant parts of the signal due to dynamic effects. However, it is also essential to choose the value for f_{cutoff} not too low to avoid significant alteration of relevant parts of the signal. Depending on the velocity of a passing vehicle, the signal part due to its static load results in low-frequency contents of the signal that could be affected by the low pass filter [5].

It is acknowledged by the authors that there are more sophisticated and accurate methods for signal processing and decomposition to extract the component representing static traffic load effects. However, the achieved accuracy of the previously described procedure is considered sufficient for the objectives of this work.

2.2. Mulitple Truck Presence

According to [6], a bridge loading event (BLE) is defined as the presence for a continuous period of time of at least one truck on the influence area of the load effect of interest, meaning two successive events are separated by a time gap with no truck present on the influence area. In other words, a BLE consists of a sequence of vehicles consecutively arriving at a bridge (in the same or different traffic lanes and driving directions) with at least one vehicle being present on the structure at each instant of time during the event. In the context of multiple truck presence evaluation, BLEs can be described by following characteristic values based on the number of contributing truck vehicles:

- total number of truck vehicles forming part of the corresponding BLE [7].
- number of truck vehicles present on the bridge for a specific instant of time during a BLE.
- number of truck vehicles contributing to the maximum value of a specific load effect during a BLE [8].

While the first two values solely depend on the traffic flow and the length of the considered bridge structure (response independent characterization), the third value is specific to a certain load effect, and hence depending on the structural response (for the same BLE, this value can vary for different load effects).

BLEs can be further categorized into following types, based on their transverse location and relative driving direction on the bridge:

- in-lane event, with multiple truck presence on the bridge within the same traffic lane
- overtaking event, with multiple truck presence on the bridge parallel on adjacent traffic lanes in unidirectional traffic
- meeting event, with multiple truck presence on the bridge parallel on adjacent traffic lanes in bidirectional traffic

Arbitrary combinations of the different event types are also possible.

For the scope of this work, multiple truck presence is evaluated based on monitoring data from both structural and traffic monitoring. Data from traffic monitoring provides detailed information on the traffic flow over the bridge, with timestamps for every passing vehicle indicating its entrance to and exit from the measurement section. Knowing the bridge length, the location of the measurement section along the bridge, and the velocity of each vehicle, timestamps for entrance to and exit from the bridge deck can be obtained. Based on this data, detection of BLEs and their (response independent) characterization is straightforward.

Data from structural monitoring represents the structural response (e.g. strains) at selected sensor locations due to the traffic flow over the bridge. These load effect time histories contain no direct information on the causative load impact. However, data fusion from multiple sensors also allows for this data evaluation towards multiple truck presence. In a first step, the processed signal (extracted component due to static traffic loads) is analyzed to identify single BLEs. In approximative accordance with the previous definition, BLEs are identified as continuous sections of the traffic component of the strain signal exceeding a predefined threshold (continuous presence of vehicles on bridge causing significant structural response). For each identified BLE, number and relative position of trucks on the bridge contributing to the maximum load effect $\varepsilon_{k,max}$ measured at sensor k (*response-sensor*) at time $t_{\varepsilon_{k,max}}$ is estimated based on transverse distribution factors (TDFs) $f_{TDF,k|i}$. These factors describe the relative share of structural response $\varepsilon_i(t = t_{\varepsilon_{k,max}})$ for a representative set of n selected sensors (*TDF-sensors*) at same longitudinal but different transverse positions and indicate the transverse position of passing vehicles:

$$f_{TDF,k|i} = \frac{\varepsilon_i(t = t_{\varepsilon_{k,max}})}{\sum_{j=1}^{n} \varepsilon_j(t = t_{\varepsilon_{k,max}})}. \quad (1)$$

This concept is based on the assumption of linear elastic structural behavior under usual traffic loading. In this case, the transverse distribution of structural response depends only on the transverse position of passing vehicles and not on their total weight [9]. The knowledge of this (response dependent) characterization of BLEs is essential for subsequent extreme value analysis (EVA), as different types of BLEs represent different loading processes to be accounted for separately.

2.3. Extreme Value Analysis

For EVA, two different methods are applied based on results from previous works [10, 11], the block maxima (BM) method with fit of generalized extreme value (GEV) distribution and the level crossing counting (LCC) method with fit of Rice's formula.

By applying the BM method, data from load effect time histories is blocked into intervals of a chosen size. The maxima in each interval are determined, generating a series of BM. A GEV distribution can then be fitted to this series [12]. By differentiating the load effects according to the underlying BLE types, separate BM series can be obtained. A different GEV distribution is fitted to each of these series, jointly composing a composite distribution model for the BM series from a mixture of different BLE types. Each BLE type considered for the composite distribution model must occur at least once per block [6]. Statistical inference is performed applying maximum likelihood estimation to obtain the parameters of the fitted GEV distributions. The estimation is performed by minimizing the respective negative log-likelihood expressions for the BM data.

For the LCC method, Rice's formula is fitted to the upper tail of an outcrossing rate histogram. Performing LCC, the number of times is counted at which positive values are crossed upwardly in a load effect time history. By normalizing the resulting level crossing histogram to the time history length, the outcrossing rate histogram is obtained, representing for each level the mean rate of its crossing during the reference period. Rice's formula describes the mean rate of upcrossing for a certain level during a reference period and is fitted to the outcrossing rate histogram. Rice's formula is fitted only to the significant tail regions, and the proper choice of the starting point for Rice's formula fit is crucial to the method. It should be as low as possible to ensure sufficient representativeness for statistical extrapolation but not too low to provide still a reasonable approximation of the significant tail region. An optimal starting point can be identified by evaluating the goodness of fit using a modified Kolmogorov test. Statistical inference is performed applying the least square method to obtain the parameters of the fitted Rice's formula. [13]

3. Bridge Structure and Monitoring

3.1. Bridge Structure 29/1

Bridge structure 29/1 is an overpass of federal highway A92 between the cities of Deggendorf (DEG) and Munich (MUC) in the Southern part of Germany, crossing an outlet ditch in five spans of uniform length of about 16 m. The bridge comprises two separate, identical superstructures, each carrying the roadway for one driving direction with a standard configuration of two traffic lanes plus emergency lane. The cross-section of each superstructure consists of five precast prestressed concrete t-beam girders of 69 cm height with a cast-in-situ slab of 23 cm height on top. The precast girders lie on elastomer bearings and cross each a single span without a rigid connection between them from one span to the next. Only the in-situ slab on top is continuous over all five spans. This design reduces the superstructure's stiffness at the piers, making each span act approximately as an independent single-span system by itself. The total width of one superstructure is 15.35 m, the width of the roadway is 12.0 m (refer also to Figures 1 and 2).

3.2. Alternating Lane Configurations

Federal highway A92 can be considered a minor section within Germany's highway network, with moderate traffic volumes. Throughout the year 2019, construction works for renovation of the roadway are carried

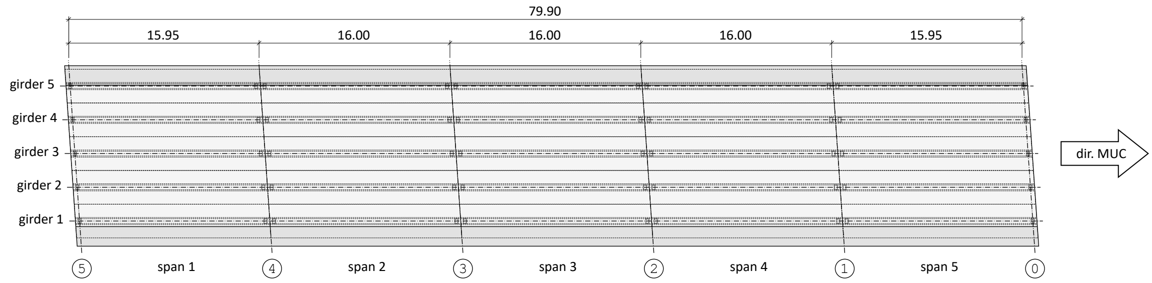

Figure 1. Top view of bridge structure 29/1.

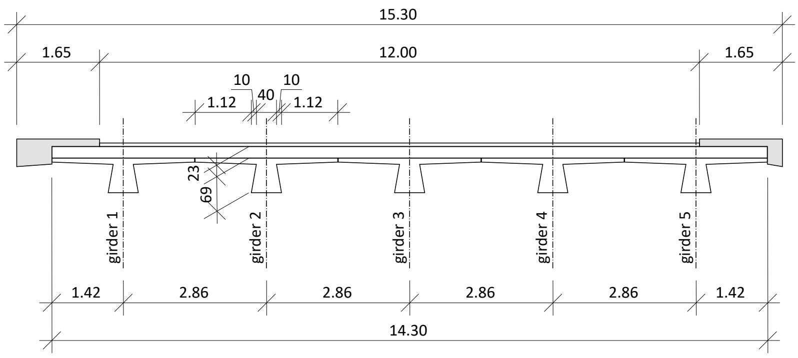

Figure 2. Section of bridge structure 29/1.

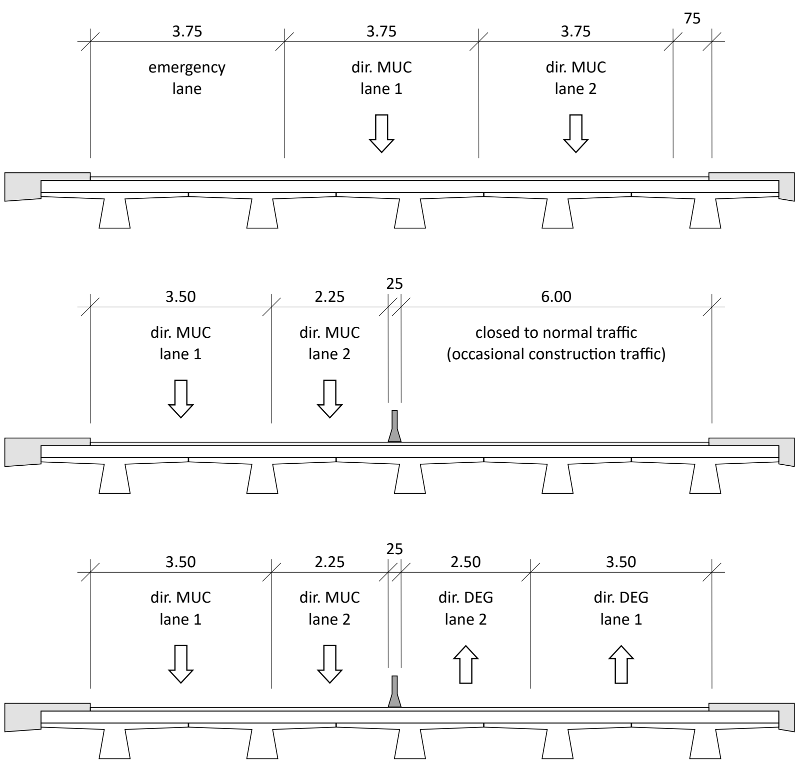

Figure 3. Lane configurations LC_{stan} (top), $LC_{mod,uni2}$ (middle), and $LC_{mod,bi4}$ (bottom).

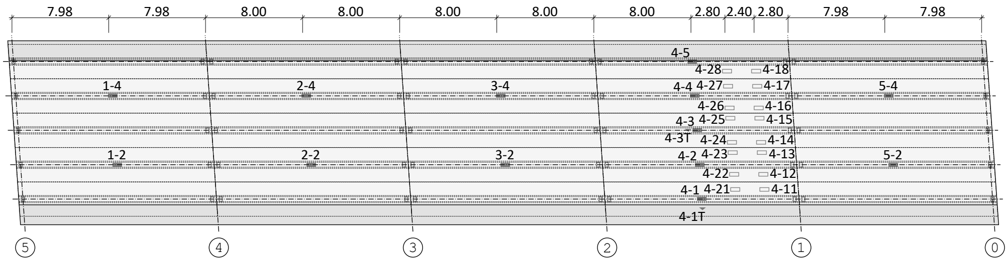

Figure 4. Overview of sensor layout of structural monitoring at bridge structure 29/1.

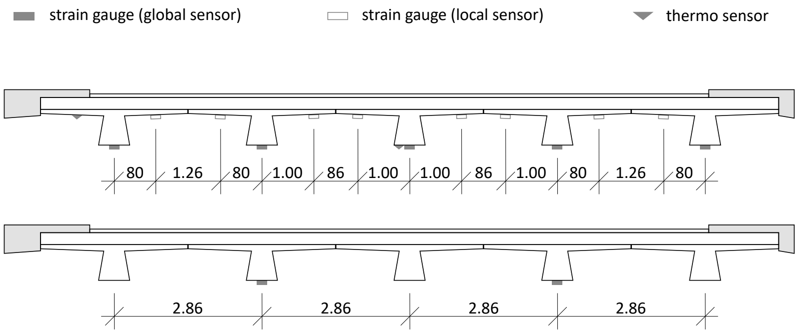

Figure 5. Sensor locations within bridge section of span no. 4 (top) and remaining spans (bottom).

out in the section of the highway where bridge structure 29/1 is located, leading to alternating lane configurations on the bridge. Besides the standard configuration of unidirectional traffic with two traffic lanes plus emergency lane per superstructure (LC_{stan}), a modified unidirectional two-lane configuration with reduced roadway width ($LC_{mod,uni2}$) and a bidirectional four-lane configuration on a single superstructure with closure of the second superstructure ($LC_{mod,bi4}$) occur throughout the construction works (Figure 3). Even though a part of the roadway is closed for regular traffic in configuration $LC_{mod,uni2}$, construction vehicles pass the bridge in this part

For expected multiple truck presence on the bridge, the occurrence of in-lane events is excluded from the scope of this work. Due to the short span length of 16 m and the approximate independence of each span from the rest of the structure (refer to Section 3.1), the influence line for the considered load effects (strain at bottom of girder at mid-span) is of restricted length. Hence, the contribution of an additional vehicle in the same lane is not significant. In this case, the characteristics of the loading process for in-lane events are similar to those of single vehicle events (SVEs). Furthermore, overtaking events for $LC_{mod,uni2}$ and $LC_{mod,bi4}$ are likely not to occur due to spatial constraints by the reduced roadway width, making it almost impossible for two truck vehicles passing the bridge parallel in usual velocities. Therefore, overtaking events are expected only for LC_{stan}. Additionally, multiple truck presence is expected for $LC_{mod,bi4}$ by meeting events in the bidirectional traffic. Besides occurrence due to regular highway traffic, the occasional passing of construction vehicles on the closed part of the roadway in configuration $LC_{mod,uni2}$ also poses a source of multiple truck presence on the bridge.

3.3. Structural Monitoring

The sensors for structural monitoring are installed on the northern superstructure, which carries the traffic with driving direction towards MUC. The monitoring concept comprises 31 sensors (29 strain gauges, two thermal sensors). The sensor layout of the strain sensors consists basically of two components: sensors for global structural response at bottom of webs of t-beams at mid-span, and sensors for local structural response at bottom of flange of t-beams at quarter-span (refer to Figures 4 and 5). The layout was designed for the realization of brigde weigh-in-motion (BWIM). The BWIM application and evaluation of related results are, however, beyond the scope of this work. In the following, the focus is on strain data from three global sensors in span no. 4 (sensors 4-2, 4-3, and 4-4).

For the signal processing (Section 2.1), the block size for the mean filtering is chosen to 10 min. The cutoff frequency f_{cutoff} for the low pass frequency filtering is chosen based on natural frequencies of the monitored structure. The eigenvalues of the structure are determined using operational modal analysis (OMA), and are about 6.7 Hz and 7.7 Hz for the first two relevant eigenmodes [14]. For further analysis, f_{cutoff} is chosen as 6.0 Hz.

The TDF threshold values for response dependent characterization of BLEs identified from structural monitoring data are derived from proof load testing of the bridge. Multiple runs with three different proof load vehicles with known weights and dimensions are

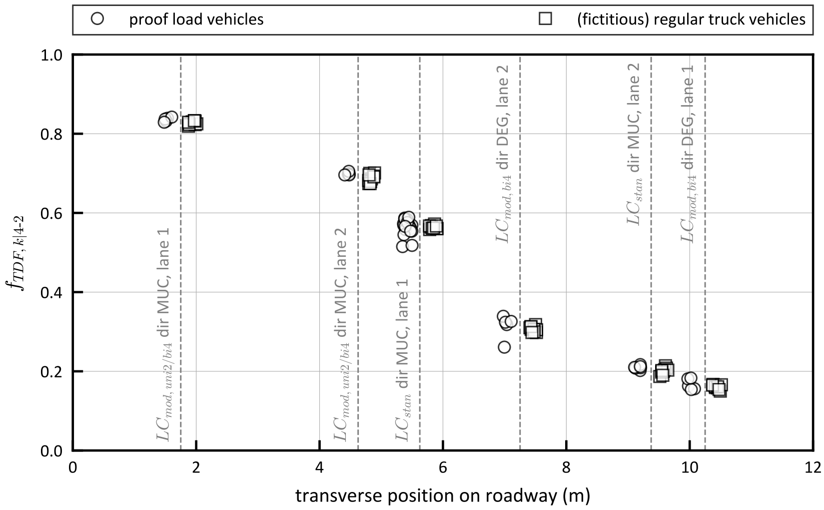

Figure 6. TDFs $f_{TDF,k|4\text{-}2}$ from proof load testing and evaluation of regular truck vehicles with reference influence line (RIL).

vehicle	**axle weight** (t)	**spacing** (m)
crane 1	12.0/12.0/12.0/12.0	1.65/1.90/1.75
crane 2	11.6/11.5/12.6/12.5	1.65/2.05/1.65
truck	7.9/8.7/9.4/6.1	1.35/3.00/1.80

Table 1. Parameters of proof load vehicles.

performed (refer to Table 1). Based on the RILs derived from the strain data of the proof load events [5], additional fictitious load patterns representing truck vehicles from regular traffic are investigated (refer to Table 2).

Theoretically, TDFs can be evaluated for any set of TDF-sensors at same longitudinal but different transverse positions, according to Equation (1). For the scope of this work, the set comprising sensors 4-2 and 4-4 proved to be a proper choice for TDF-sensors able to differentiate clearly between the several transverse position in different traffic lanes for different lane configurations (refer to Figure 6 for TDFs $f_{TDF,k|4\text{-}2}$, values for $f_{TDF,k|4\text{-}4}$ complement to 1). For all considered response-sensors $k \in [4\text{-}2, 4\text{-}3, 4\text{-}4]$, instants $t_{\varepsilon_{k,max}}$ are nearly identical, and therefore $f_{TDF,k|i}$ result in equal values.

3.4. Traffic Monitoring

Besides the previously described structural monitoring, an additional traffic monitoring unit is installed. This unit consists of a laser scanner for vehicle detection, counting, and detailed classification and a webcam providing image data of the traffic flow on the bridge for comparison and verification purposes. The monitoring unit is placed on top of a telescoping mast right next to the northern superstructure in span no. 4, about 8 m above the top of roadway (see Figure 7). Due to lateral installation of the monitoring unit, this height is necessary to avoid shadowing

ID	**axle weight** (t)	**spacing** (m)
11	9.0/11.0	4.5
12	6.8/7.6/5.5	4.3/1.3
1111	10.3/14.9/7.6/7.2	4.9/6.5/5.0
1211	8.4/10.3/6.4/7.8/7.1	4.6/1.3/5.2/4.6
112	12.2/12.4/7.6/7.8	3.7/6.6/1.3
113	8.3/11.2/6.8/6.8/6.8	3.7/5.6/1.3/1.3
14	12.0 (all)	2.6/1.7/1.7/1.7
222	12.0 (all)	1.9/2.9/1.7/2.6/1.7
111	6.0/8.3/10.8	5.9/6.0
11	7.2/12.8	5.9

Table 2. Parameters of regular truck vehicles (data adopted from [1, 4], ID corresponds to sequence of axle groups with number of axles per group).

effects and provide the best possible quality of vehicle detection and classification.

Figure 7. Traffic monitoring unit next to bridge.

The laser scanner used in the measurement unit is the profiling system *TIC501* from *SICK AG*. Its 2D light detection and ranging (LIDAR) sensor works with multiple echo technology, making it robust against atmospheric exposure. It detects the travel lane of the vehicles and scans passing vehicles up to 100 times per second, creating a 3D point cloud of the vehicles' silhouette serving as a base for further classification. The profiling system can cover up to four traffic lanes. Furthermore, vehicle dimensions and velocity are recorded, as well as the timestamp of entrance to and exit from the scanning section allowing for determination of inter-vehicle gaps and reconstruction of actual traffic flow. [15]

4. Results from Monitoring Data Analysis

For the scope of this work, complete daily data sets for the different lane configurations for the following periods are available:

- LC_{stand}: 22.11.2019 until 18.12.2019
- $LC_{mod,uni2}$: 25.10.2019 until 18.11.2019
- $LC_{mod,bi4}$: 11.10.2019 until 23.10.2019

For further analysis, only data from working days within the mentioned periods is considered.

4.1. Multiple Truck Presence on the Bridge

As previously stated in Section 3.2, the possibility of overtaking events in the same driving direction for $LC_{mod,uni2}$ and $LC_{mod,bi4}$ can be excluded due to spatial constraints by the reduced roadway width. Analysis of the traffic monitoring data for the different lane configurations confirms this statement (Figure 8).

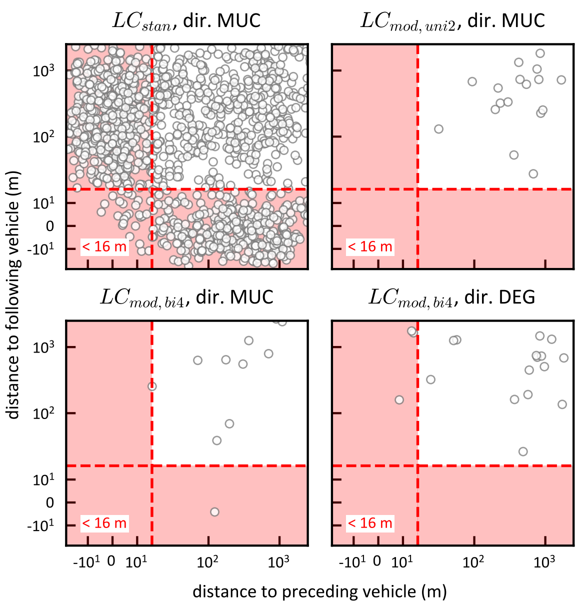

Figure 8. Spatial gaps of vehicles on fast lane to adjacent vehicles in slow lane, for different lane configurations.

For each truck traveling on the fast lane, the spatial gap to its preceding (distance from front of vehicle in fast lane to end of vehicle in slow lane) and following

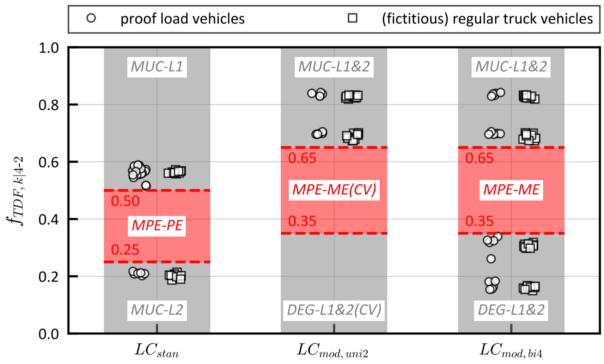

Figure 9. Definition of threshold values for MPE identification for different lane configurations.

(distance from end of vehicle in fast lane to front of vehicle in slow lane) truck on the slow lane is determined, based on timestamps and velocities from the laser scanner data record. If the vehicle in the fast lane is overtaking another vehicle on the slow lane while crossing the bridge, either of these spatial gaps takes a small value (threshold value of 16 m corresponding to span width of bridge structure). The results in Figure 8 show that in general, there are only very few vehicles traveling in the left lane for $LC_{mod,uni2}$ and $LC_{mod,bi4}$ being hardly part of an overtaking event. For LC_{stan}, it can be seen, however, that significantly more vehicles travel on the fast lane and that the vast majority of them are overtaking other vehicles.

Based on the evaluation of TDFs for proof load testings and fictitious regular truck vehicles (see Section 3.3), and explanations regarding possible types of multiple presence events (MPEs) for the different lane configurations (see Section 3.2), appropriate threshold values for $f_{TDF,k|4\text{-}2}$ are defined to allow for MPE identification (refer to Figure 9). For the different lane configurations, following classifications of BLEs are specified:

- LC_{stan}: SVEs on lane 1 or lane 2 (*MUC-L1* and *MUC-L2*), MPEs as overtaking events (*MPE-OE*)
- $LC_{mod,uni2}$: SVEs on direction MUC (*MUC-L1&2*), SVEs due to possible construction vehicles on direction DEG (*DEG-L1&2*), MPEs as meeting events with regular traffic on direction MUC and possible construction vehicles on direction DEG (*MPE-ME(CV)*)
- $LC_{mod,bi4}$: SVEs on direction MUC and direction DEG (*MUC-L1&2* and *DEG-L1&2*), MPEs as meeting events (*MPE-ME*)

Due to spatial constraints for $LC_{mod,uni2}$ and $LC_{mod,bi4}$, and the resulting decreased probability of trucks travelling in the fast lane, no differentiation is made for these lane configurations for vehicles travelling either in lane 1 or lane 2 within the same driving direction.

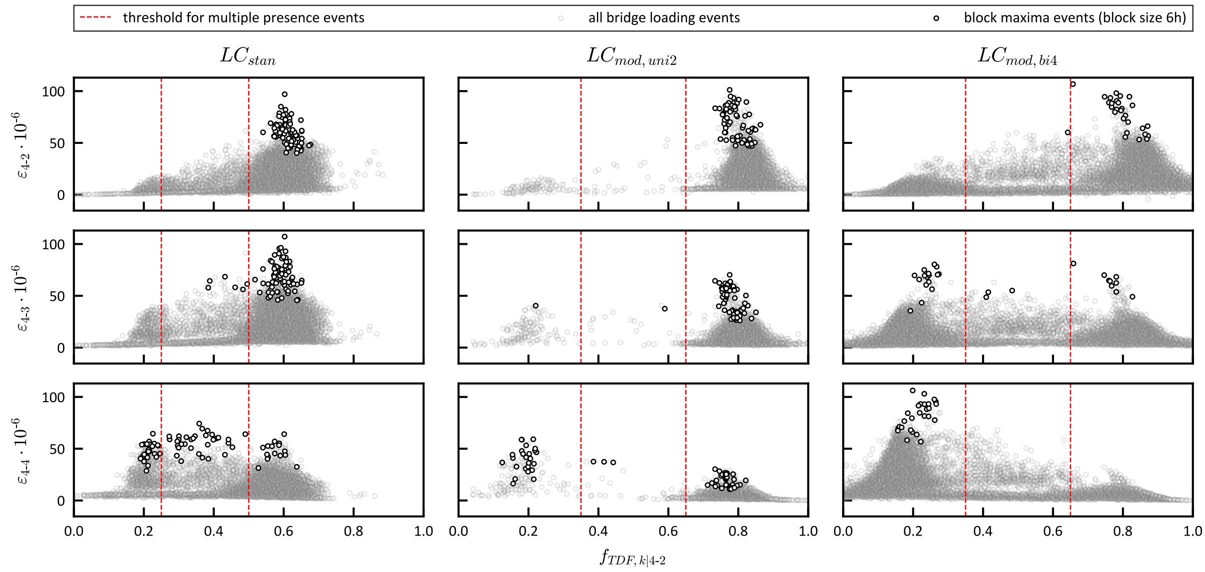

Figure 10. TDFs $f_{TDF,k|4\text{-}2}$ evaluated for all BLEs identified from structural monitoring data of working days (BM events with blocks size 6 h highlighted), for different lane configurations and considered response-sensors.

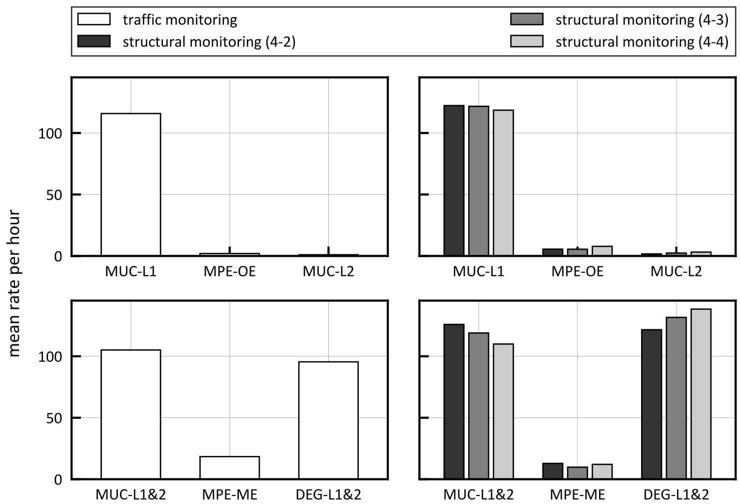

Figure 11. Mean hourly occurrence rates of different BLE types for lane configurations LC_{stan} and $LC_{mod,bi4}$, evaluated for working days.

The TDF evaluation for the three different lane configurations is shown in Figure 10. Based on the available data from structural monitoring, relevant BLEs are identified and classified according to the previously defined criteria for TDFs. The results generally confirm the choice of TDF-thresholds for MPE identification. For all three lane configurations, dense accumulations of data points can be observed beyond the thresholds, representing the respective SVEs dominating (in the sense of occurrence rates) the bridge loading process in all cases. MPE occurrence in significant numbers is observed for lane configurations LC_{stan} (overtaking events) and $LC_{mod,bi4}$ (meeting events). For lane configuration $LC_{mod,uni2}$, the vast majority of BLEs are SVEs on driving direction MUC. However, due to the occasional passing of construction vehicles on the closed part of the roadway, small numbers of SVEs on driving direction DEG and MPEs (meeting events) can be observed.

For further quantification of MPE occurrence, the mean hourly occurrence rate of SVEs and multiple truck presence on the bridge is evaluated and compared for lane configurations LC_{stan} and $LC_{mod,bi4}$ (Figure 11). While slightly differing in absolute numbers, the occurrence rates obtained from traffic monitoring (based on data from laser scanner) and structural monitoring (based on data from strain sensors) show similar tendencies. It can be observed that MPE occurrence rates are significantly higher for bidirectional traffic (meeting events) than for unidirectional traffic (overtaking events), but still relatively small compared to occurrence rates of SVEs.

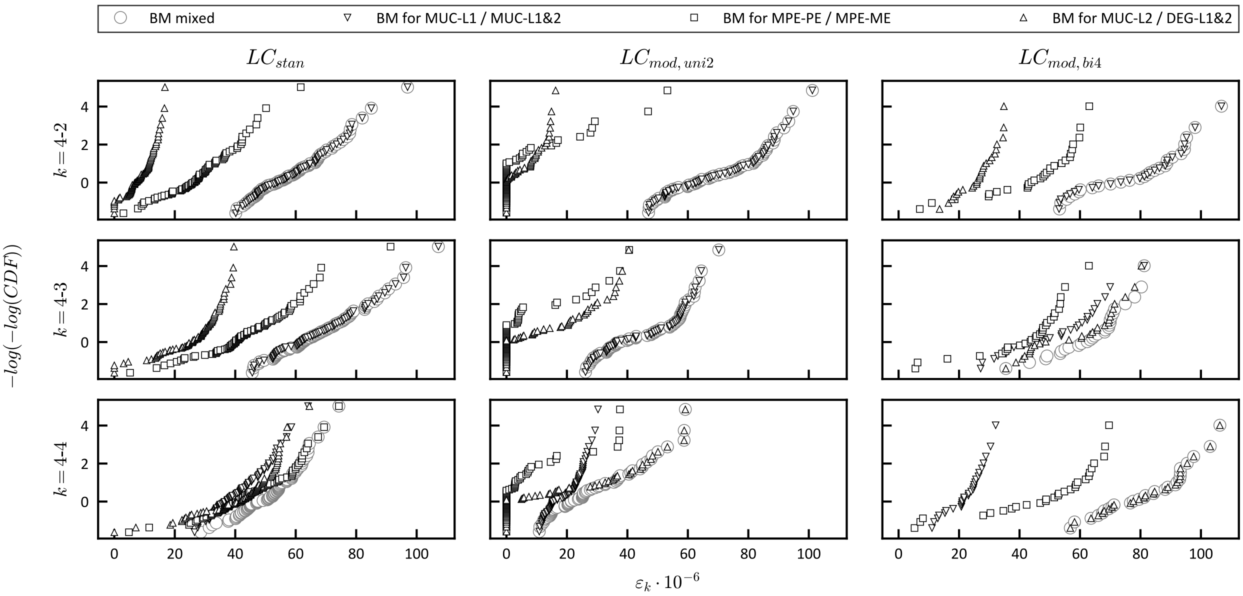

Figure 12. BM data (block size 6 h) of working days for considered sensors and different lane configurations; with and without differentiation of different BLE types.

4.2. Load Effects and Extreme Value Behavior

For analysis of the resulting load effects and the impact of multiple truck presence, BM data (block size 6 h) is obtained from the structural monitoring data for the different lane configurations, with and without differentiation of different BLE types (refer to Figure 12). The BM data reveals only for a few cases actual significance of MPEs, e.g. for sensor 4-4 in LC_{stan}. In most cases, the bridge loading process is dominated by SVEs, primarily by one SVE type alone (e.g. MUC-L1 for sensor 4-2 in $LC_{mod,stan}$) or sporadically by a mixture of two SVE types (e.g. MUC-L1&2 and DEG-L1&2 for sensor 4-3 in $LC_{mod,bi4}$). These observations are supported by illustrations in Figure 10 for the highlighted BM data. Regarding lane configuration $LC_{mod,uni2}$ it can be observed that the regular traffic (MUC-L1&2) dominates the structural response of sensors 4-2 and 4-3, while data from sensor 4-4 reveals the dominant influence of the occasional construction vehicles passing the bridge on the closed part of the roadway. Concerning the absolute load level, data shows only slight variation with changing lane configurations for sensor 4-2. In contrast to that, sensor 4-3 experiences its most severe loading for LC_{stan}, whereas sensor 4-4 faces the heaviest loading for $LC_{mod,bi4}$. This has mainly to do with the change of transverse position of the traffic lanes on the roadway relative to the single sensor locations, as for all three sensors, the data shows no significant impact of MPE for lane configurations leading to the most adverse loading.

Regarding the extreme value behavior, extrapolated values with a return period of 1000 years are determined applying the different methods mentioned in Section 2.3. Due to the limited amount of available data for the BM method, a choice of a usual block size of 1 d is not feasible. However, a block size chosen too small (e.g. 1 h) might not fulfill the requirement of statistical independence of the different BM events necessary for application of BM method for EVA. As a compromise, a block size of 6 h is chosen for the scope of this work. For lane configuration $LC_{mod,uni2}$, extrapolation is performed for both cases considering and neglecting BLEs resulting from construction vehicles on the closed part of the roadway. The extrapolation results are shown in Table 3.

	method	ε_{4-2}	ε_{4-3}	ε_{4-4}
LC_{stan}	BM-mix	146.9	144.6	74.3
	BM-comp	146.9	154.7	89.1
	LCC	158.9	156.1	121.6
$LC_{mod,uni2}$ (incl. CV)	BM-mix	110.8	75.1	342.2
	BM-comp	–	–	–
	LCC	130.3	92.4	114.7
$LC_{mod,uni2}$ (excl. CV)	BM-mix	110.8	75.3	33.1
	BM-comp	110.8	75.3	33.1
	LCC	130.3	92.5	42.3
$LC_{mod,bi4}$	BM-mix	112.0	83.4	111.5
	BM-comp	111.6	90.3	111.5
	LCC	145.2	122.2	149.4

Table 3. Extreme value estimates with different methods for 1000 years return period.

It can be observed that both BM methods with (*BM-comp*) and without (*BM-mix*) differentiation of different BLE types lead to quite similar results in many cases. The reason for this is that the bridge loading process is dominated by a single BLE type in most cases, as previously explained. Both BM methods face problems for $LC_{mod,uni2}$ when considering BLEs due to occasional construction vehicles. Due to their irregular occurrence on the bridge, the related BLE types do not occur in every block, making application of method BM-comp unfeasible. Moreover, structural response at sensor 4-4 is dominated by two different BLE types in this lane configuration, causing ill-conditioning for the method BM-mix. In general, the most robust results seem to be provided by LCC method, which makes more use of the data by considering each loading event, and not just a few per block. A tendency of slightly higher extrapolated values compared to BM methods can be observed. Altogether, the previously identified tendencies for the measured load effects are approximately reflected in the results of EVA again. Also, the importance of BLE due to occasional construction vehicles for sensor 4-4 in $LC_{mod,uni2}$ is clearly shown. However, in parts significant variation of results between the different methods of EVA can be observed.

4.3. Discussion of Results

Analysis of traffic flow characteristics and resulting occurrence rates of multiple truck presence on the bridge show that the modified lane configurations have a contrastive impact. On the one hand side, reduced available roadway width leads to a disappearance of overtaking events compared to the standard lane configuration. However, in the case of bidirectional traffic on the structure, additional multiple presence events occur in the form of meeting events. The mean occurrence rates of meeting events in bidirectional traffic are significantly higher than those of overtaking events in unconstrained unidirectional traffic. This can be explained by the different volumes of available truck vehicles potentially involved in the respective MPEs. While in unconstrained unidirectional traffic only relatively few truck vehicles travel on the left lane and possibly are part of an overtaking event, a significantly larger number of truck vehicles passes the bridge in the opposite direction in bidirectional traffic that potentially cause a meeting event. The correlation effect of vehicles involved in overtaking events – if a truck travels on the left lane, it is very likely part of an overtaking event instead of crossing the bridge alone (data analysis shows that 65 % to 75 % of trucks traveling in the fast lane are involved in an overtaking event) – usually would lead to a higher occurrence rate. However, this effect is outweighed in this case by the significant increase in the volume of possibly involved truck vehicles in meeting events (even though here the vehicles are entirely uncorrelated).

Regarding the resulting load effects, it is found that modifications of the lane configuration on the bridge noticeably alter the characteristics of the bridge loading process. However, the related change in occurrence rates of multiple presence events has only for a few cases of considered load effects and lane configurations significant impact on the extreme value behavior. Due to the distinct biaxial structural behavior of the considered bridge structure in combination with the limited span width compared to the usual length of regular truck vehicles, it is rather the change of transverse position of the traffic lanes on the roadway playing a more dominant role compared to multiple truck presence. Therefore, the loading process for the different lane configurations is dominated by single vehicle events in most scenarios. For bridges with different dimensions and structural systems (uniaxial rather than biaxial structural behavior of superstructure), opposite characteristics are expected, with multiple truck presence playing a more dominant role in the loading process. A particular case is observed in the study for the modified unidirectional two-lane configuration, with occasional bridge crossings of construction vehicles on that part of the roadway closed to regular traffic. Even though their occurrence is sparse, they dominate the loading process for specific load effects.

Concerning the results of extreme value analysis, in parts significant variation of results between different extrapolation methods can be observed. This raises the question of accuracy of the different extrapolation methods and their appropriateness for application in this study, especially in the context of the relatively small extent of available monitoring data and the limited degree of knowledge on the actual load impact leading to the measured structural response (knowledge on underlying loading processes). The LCC method with fit of Rice's formula makes the best use of the available data by considering each loading event and seems to provide the most robust results over the range of investigated load effects and lane configurations. However, the evaluation of the accuracy of the individual extrapolation results is beyond the scope of this study.

5. Conclusions

The presented study analyzes data from bridge monitoring along federal highway A92 in Southern Germany. The data covers standard and different modified lane configurations due to construction works.

Regarding the impact on multiple truck presence on the bridge, the results from the study confirm the basic assumption from code background works that a realistic, reduced width of the fast lane in modified lane configurations effectively prevents truck vehicles from overtaking. Analysis of the monitoring data proves an almost complete disappearance of overtaking events for both modified configurations in this study. Furthermore, it is found that the mean occurrence rates of meeting events in bidirectional traffic are significantly higher than those of overtaking events in unconstrained unidirectional traffic. This observation can be considered representative for typical highway traffic characterized by small ratios of truck vehicles traveling on the left lane compared to the right lane (for unconstrained unidirectional traffic) and similar truck traffic volumes for both driving directions (for bidirectional traffic).

How the change of lane configuration alters the bridge loading process heavily depends on its governing aspects, which are determined by the characteristics of the bridge structure itself. For the bridge in this study (distinct biaxial structural behavior, short span width), single vehicle events play the dominant role in most scenarios. The loading processes for the considered load effects are governed rather by the change of transverse position of the traffic lanes on the roadway than by multiple truck presence on the bridge. Therefore, it is crucial for traffic load modeling to accurately represent the single truck vehicles' parameters (i.e. axle weights and spacings) and their transverse position on the roadway. In the particular case of a lane configuration with partial closure of the roadway, it is either essential to consider possible construction vehicles in this part or to ensure that the closed part of the roadway is, in fact, free of any type of vehicle (e.g. in case of partial roadway closure as a constraining measure to reduce the level of traffic loading on the bridge).

Extreme value analysis proves to be challenging due to the relatively small extent of available data and limited knowledge on underlying loading processes. Application of level crossing counting method with fit of Rice's formula and classification of bridge loading events based on transverse distribution factors towards composite distribution models for block maxima aim to make the best use of the available data. Nevertheless, results from different extrapolation methods show considerable variation, and straightforward identification of the most accurate and reliable results is not feasible. Therefore, statistical extrapolation is to be performed with great care. Further research efforts beyond the scope of this paper are necessary, i.e. towards adopting techniques allowing for comparing the accuracy of the results from the different extrapolation methods based on a given data set of limited extent.

Further future research efforts should focus on extending investigations on the impact of modified lane configuration on the bridge loading process to a broader range of different types of bridge structures. Especially for bridge superstructures with a rather uniaxial than biaxial structural behavior, multiple truck presence is expected to play a more dominant role in the loading process. Moreover, a more realistic consideration of scenarios with modified lane configurations could exploit further potential in the scope of object-specific traffic load models. By quantifying the expected occurrence periods of different modified lane configurations throughout regular bridge lifetime, and consistent consideration in bridge load modeling besides the standard configuration based on findings from this study, a more accurate estimate of extreme bridge loading throughout the service life of a bridge structure can be obtained.

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