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TRAFFIC LOAD MODEL CALIBRATION AND COMPARISON TO EVOLVING TRAFFIC LOADS IN 2014–2018

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Abstract. The national calibration of Eurocode load model 1 (LM1) for road bridges was made by a calibration of the load effects of LM1 against the corresponding load effects of a former load model used in Finland. Due to the increased gross vehicle weights in legislation, a national calibration of LM1 was necessary and the stochastic simulation was needed. The aim of this study is to generate a traffic model together with a predictive model for simulation purposes by using and combining long-time monitoring data measured on a road network in different surveys. In this paper, the performance of the predictive model of increases in axle loads and gross vehicle weights is evaluated against short-term bridge weight in motion (BWIM) measurements. The results achieved with a simulation can be used to gain more information of statistical parameters and the evolution of load effects caused on bridges by road traffic in Finland. The simulation model presented in this study served as a basis for updated national calibration of load model LM1. The follow-up comparison between predictive model and traffic monitoring shows the suitability of the estimation of the evolution of traffic loads and also necessity of the raise of LM1.

Keywords: bridge, traffic loads, weight-in-motion, statistics, load model, simulation.

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Introduction

Considerable growth in industrial activities and the volume of road transportation of goods have caused a need for allowance of heavier lorries on the road network to make the road transport more economical. However, the design of infrastructure is done for traffic loads in the past and with the assumption of certain increases in traffic loads. The Finnish national regulations concerning the use of vehicles on the road changed in November 2013. The updated Decree on the Use of Vehicles on the Road (Decree on the Use of Vehicles on the Road, 1992) allowed heavier total masses of vehicles and heavier masses of single, tandem and tridem axles. The increase in the allowable masses was about 5…15% in comparison with past regulations. At the time, a questions arose: What does that mean for loads of bridges? Does the existing load model correspond to the actual traffic loads at the present time or in the future?

The basic traffic load model of Eurocode is based on a monitoring period of several weeks near Auxerre, France in the 1980s (Babu et al., 2019). The Eurocode-standards with a respective traffic load have been used in the design of bridges in Finland since 2010. The traffic loads used in design were calibrated according to former national guidelines; no comparison based on surveys of real traffic was made in Finland. There is considerable difference in the composition of traffic between Europe and Finland; for example, lorries with a semitrailer are more common in Europe, whereas lorries with a full trailer in Finland are more common. Also, there is a substantial difference in allowed axle loads and gross vehicle weights /GVW), including new high capacity transport vehicles up to 76 tons. The verification of a bridge load model was needed to assess the effects of the change of Decree on the Use of Vehicles on the Road (Decree on the Use of Vehicles on the Road, 1992). First, there was a need to assess the current situation based on traffic data prior to the change (before 2013).

At the time of the legislation change there was neither statistical model nor BWIM-data available regarding Finnish traffic. For the stochastic analysis of structural safety and national calibration of load model, there was a need for a statistical model of traffic load effects. The stochastic model should be constructed with data available at the time: axle mass studies (AMS) and automated traffic monitoring (ATM) records. The assessment of the safety, reliability and robustness of the structure depends on how accurate the characteristics of loads affecting a structure can be predicted. Especially in the analysis of existing structures, the accurate modelling of traffic load can lead to considerable savings by avoiding unnecessary bridge refurbishments and replacements. In this paper, the method for the generation of traffic for traffic load simulation and the prediction of the structural effects of the change in allowable axle masses based on available data is presented. The comparison of a predictive model, which was used in the calibration of LM1 and data from BWIM-measurements, is also presented.

In stochastic analysis, the modelling of traffic load effects on internal forces and stresses of structural systems and details plays a significant role. A stochastic simulation is widely used for the prediction and assessment of the extreme traffic load effects on bridges and other road infrastructure (OBrien, Lipari, et al., 2015, Chen & Wu, 2011). For a simulation, a suitable database is needed to model the traffic flow characteristics. For free flowing traffic the importance of multiple lorry presence in traffic load calculation is presented (Caprani et al., 2002, Caprani et al., 2008). The traffic data of short time can be used together with Monte Carlo techniques to generate the database of vehicles with which an adequate amount of traffic can be achieved to identify rare traffic load effects (Shahidan et al., 2016). The effect of changes in allowed limits and evolution and considering gross-vehicle weights and axle masses of lorries is analysed based on BWIM measurements also in research (OBrien et al., 2012), in which the model of evolution of GVWs is adopted from records of different country. The performance of the model of evolving traffic loads is considered in this study with follow-up study of local traffic characteristics.

The information of Finnish highway traffic is collected with various permanent or temporary technical systems installed on road network (Finnish Traffic Administration (FTA), 2015). In time of construction of the first simulation 2014, the available data were based on ATM points and axle mass surveys (AMS). In this study, the available data are used to construct a model for the determination of the effects of road traffic on bridges. Later, the data are collected with BWIM-equipment, which provided an opportunity to follow the evolution of traffic loads over time.

The scope of this study is to assess the effects of Finnish traffic and the effects of the rise on allowed vehicle masses on bridge structures and to achieve statistical characteristics of the traffic load on bridge structures. The study consists of three different phases:

i) Simulation prior to the raise of allowed axle loads (2014);
ii) Simulation with a predictive model of future axle loads, which was the base for the calibration of load model LM1 for the design of new structures (2014);
iii) Follow-up and comparison between collected BWIM-data during the following years (2015…2018).

The study was performed by simulation of heavy traffic, based on axle mass surveys and the data collected with ATM-points i) and ii). The comparison of the simulation results and the results of simulation with a predictive model of development of axle and gross-vehicle weight (GVW) was performed using BWIM monitoring results of a short duration iii).

1. Materials and analysis of data

The data used in a simulation study are collected in separate surveys used for monitoring the characteristics of Finnish traffic. The data are measured from three different studies. The axle mass surveys (AMS) (Finnish Traffic Administration (FTA), 2015) were carried out in 1999 and 2013–2015. The data from (ATM) points were collected in 2014. The BWIM-measurements were carried out between 2014 and 2018 (Trafikia, n.d.).

1.1. Data collected in ATM-points

The automatic traffic monitoring point is based on an inductive loop pair embedded in road surface on each lane and data logger. With this arrangement it is possible to detect and record the axle configurations of crossing vehicles. The achieved data consist of a time-stamp of each axle on each loop. With post-processing methods, it is possible to extract traffic characteristics and types of crossing vehicles. The list of total 17 ATM-points with traffic characteristics is shown in Table 1.

The data extracted from ATM-measurements, which are used to construct a simulation model for traffic flow:

- Lorry density [lorries/day] (calculated from yearly traffic);
- Lorry types: trucks, trailers, semi-trailers, coaches, axle configurations;

Table 1. Relevant points of automatic traffic monitoring and traffic characteristics used in the study

ATM #	Location	Total traffic daily average	Lorries, daily average	Lorries, %	Road class	Number of lanes
168	Askisto	41 546	4065	9.8%	1	4
902	Äänekoski	5954	811	13.6%	2	2

- Density of convoys: distance between two (or more) consequent lorries < 300 m, [convoys/day];
- Distribution of inter-vehicle distances in convoys, m;
- Overall density of traffic, including passenger cars, [vehicles/day];
- Meeting and overtaking probabilities, %.

The axle loads are not recorded with an ATM-arrangement. The distributions of presented characteristics are determined based on collected data. The period of the data is one year and the data are collected from 17 different points. In this paper, the result distributions are presented in two ATM-points that are determined to be the most interesting ones. The most important ones were located on main routes (road class 1) with 2+2 lanes and (road class 2) with 1+1 lanes, respectively.

1.2. Data collected in axle mass surveys

For modelling the traffic load effects, the data about the axle masses of lorries are needed. In 2013, the only data available for this purpose were the results of the AMS, which were selected to be combined together with ATM data. No BWIM recordings before 2013 and legislation change existed. Axle mass surveys were performed on the road network in Finland. The monitoring locations were set on selected representative roads on lay-byes. The weight of lorries stopped at lay-byes was measured with the scale axle by axle to achieve the distribution of axle loads, tandem and tridem loads and gross vehicle weight. In addition, the configuration of lorry type and axle geometry was observed. The shortcoming of AMS is that they are averages over the road network and, therefore, do not present the distribution of axle masses accurately in different locations.

The variety of truck and lorry types and possible combinations is large. To simplify the traffic simulation, the most common subclasses and their percentages of lorry types were considered in the modelling. The selected lorries and trailers are presented in Table 2. In lorry types 3 and 4, the lorry consists of two parts. Each part has its own probability of occurrence.

Table 2. The most common lorry types, the relative percentage in subcategories and axle geometry of the vehicles selected for traffic simulation. Note: x – distance in m

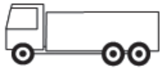
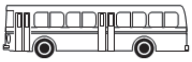
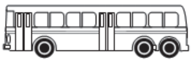
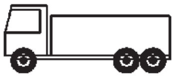
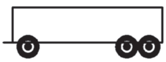
	Vehicle	Relative percentage	x_{axle}			
			x_1	x_2	x_3	x_4
1) Lorry without trailer		55.6%	0	4.5		
		37.4%	0	4.2	5.5	
		1.6%	0	4.2	5.5	6.8
		5.4%	0	2.5	5.5	6.8
2) Bus		93%	0	6.2		
		7%	0	7.2	8.6	
3) Tractor with semi-trailer		45.8%/ 54.1%	0	3.4	4.7	
			from the last wheel of tractor			
			x_1	x_2	x_3	x_4
		12.9%	5.6	7.4		
		3.3%	6.6	7.9		
		83.8%	5.6	6.9	8.2	
4) Truck and trailer		89.1%	0	4.5	5.8	
		10.9%	0	5.2	6.5	7.8
			from the last wheel of truck			
			x_1	x_2	x_3	x_4
		58.0%	5	6.3	12.2	14.2
		17.7%	5	12.2	14.2	
		12.6%	5	6.3	12.7	14
		11.7%	5	12.7	14	

Table 3. The applied changes on allowed axle weights (Decree on the Use of Vehicles on the Road, 1992) and predictive modeling of axle weight distribution after proposed change

Vehicle, axle or bogie type		Change in allowed weight, t			INCR, %
Lorry or tractor, overall	– Two axle vehicle	18	→	20	11.1
	– Three axle vehicle	26	→	28	7.7
	– Four axle vehicle	32	→	35	9.4
	– Five axle vehicle	38	→	42	10.5
Vehicle combination, overall	– Seven axle vehicle	60	→	64	6.7
	– Eight axle vehicle (1	N/A	→	68	–
	– Nine axle vehicle (1	N/A	→	76	–
Axles, and bogies	– Single axle (2	10	→	10	–
	– Two axle bogie (tandem)	19	→	21	10.5
	– Three axle bogie (tridem)	24	→	27	12.5

1.3. The change in allowed axle weight in legislation

In Table 3, the applied changes in legislation of allowed axle weights are presented. In the last column, the relative increase in these weights is calculated. Completely new allowed vehicle types are also presented, notation 1. Although the increase in the allowed axle weight on a single axle was not proposed, it is presumable that the change in legislation also has an effect on the distribution of a single axle weight, notation 2. For example, the increase in the gross vehicle weight of a 2-axle vehicle means the increase in a single axle weight. The weights of the front most axles of tractors are not assumed to increase significantly because the self-weight of a vehicle forms a majority of this.

1.4. Data collected in BWIM

BWIM measurements were performed at several locations (Table 4), in the Finnish road network (Trafikia, 2016). The measurements were carried out by attaching strain gauges on the bottom of a bridge slab and analysing the strain history caused by flowing traffic. The output values of the monitoring are static axle- and gross-vehicle weights as the dynamic effect is filtered out by post-processing software (Trafikia, 2016).

Table 4. Locations and number of daily lorries and observed averages of daily maximums of gross vehicle weights (ADM-GVW) of BWIM-bridges. Note: * traffic on lanes in the same direction

			2014		2015		2016		2017		2018	
Road	Location	# of lanes	n	ADM GVW, kN	n	ADM GV, kN	n	ADM GV, kN	n	ADM GVW, kN	n	ADM GVW, kN
VT 4	Äänekoski	2	901	666	937	772	927	919	–	–	1160	913
180	Kaarina	2	637	646	–	–	–	–	–	–	–	–
E75/E8	Olhava	2	914	–	1074	777	–	–	–	–	1012	1022
E8	Pirttikylä	2	340	–	–	–	–	–	–	–	–	–
R3	Ring III East	2*	2494	625	1958	700	–	–	2446	897	–	–
R3	Ring III West	2*	2086	668	2005	759	–	–	2106	809	–	–

The data achieved with BWIM consist of a time stamp, axle weights, speed, distances between the axles and a lane along which the vehicle crosses the bridge. The minimum weight of a vehicle considered to be a lorry is 10 tons. The data gathering neglects the meeting and overtaking situations as they disturb the monitoring, consequently the overall effect of combined effects of traffic on the lanes is not recorded. Still, it is possible to compile the daily traffic on each of the lanes based on these results.

The compilation of daily traffic from BWIM-data is carried out by processing the data in which one row represents one vehicle crossing the bridge. The time stamp of the vehicle is used together with the moving average speed of traffic flow to calculate the location of the first axle of a single vehicle. The recorded axle distances of the vehicle are used to determine the consequent axles and recorded axle loads are associated with those locations to form a load pattern with the length of daily traffic consisting of point loads (axles), which are referring to daily axles (see Figure 4).

2. Analysis of traffic load effects and stochastic simulation

The assessment and determination of the characteristic load effects of traffic load by measuring them directly from structures would be an enormous, nearly impossible, task due to the large variability of structures and long return periods. That is why a stochastic simulation is typically selected. The stochastic simulation, i.e., Monte Carlo

–simulation, is often used for modelling complex stochastic multivariate problems. The idea of Monte Carlo simulation is to generate variables from statistical data and perform calculations multiple times in order to achieve a statistical distribution of the result values.

The generation of randomness of the parameters in simulation is based on the generation of random numbers and the inverse cumulative probability functions of the parameter. The cumulative probability functions of parameters are achieved by determining the empirical cumulative distribution function from data obtained in different traffic monitoring methods.

The advantage of an empirical probability function in this case is that it has relatively few assumptions. In this case, the bias problem caused by estimating probabilities close to one or zero has no significant effect because the sample size in datasets is rather large and the results of the simulation are not strongly dependant on the extreme value of the single random variable.

2.1. Influence lines and structure types

In the simulation, the generated traffic flow is driven over influence lines stepwise. The selection of influence lines in Table 7 is based on reference (ENV 1991-3 Traffic Loads on Bridges Background and Notes, 1994). The total number of influence lines in the simulation is 45. The analysis is based on one-dimensional influence lines, with which it is possible to analyse and compare the most important effects for the main structural system.

Table 5. Influence lines in simulation

Structure	Internal force	Symbol	Main span lengths, m
ALL	Total load on length	Q	*L* = 10, 20, 30, 50, 100, 200
Simple Beam	Bending moment field	M0	*L* = 10, 20, 30, 50
	Shear force, support	V0	*L* = 10, 20, 30, 50
	Shear force, field	V1	*L* = 10, 20, 30, 50
Continuous 2-span beam 1:1	Bending moment, field +	M1+	*L* = 10, 20, 30, 50, 100
	Bending moment, field –	M1–	*L* = 10, 20, 30, 50, 100
	Bending moment, support	M2	*L* = 10, 20, 30, 50, 100
Continuous 3-span beam 1:1.22:1	Bending moment, field +	M3+	*L* = 10, 20, 30, 50, 100, 200
	Bending moment, field –	M3–	*L* = 10, 20, 30, 50, 100, 200

2.2. Statistical modelling of traffic parameters

The modelling of the bridge loading due to the presence of multiple lorries on bridge is performed by considering the probabilities of the occurrence of lorries in multiple lanes, convoys of lorries and the correlation of the GVWs of the lorries and trailers.

The meeting and overtaking situations between lanes (i.e., lorries or convoys affecting, simultaneously, on lanes) are generated based on data extracted on ATM-points. The event in recorded traffic data is considered to be 'meeting' or 'overtaking' if there is one vehicle (or convoy) on a monitoring point on lane 1 and another vehicle (or convoy) on lane 2 with an opposite direction within 300 m from the monitoring point.

In ATM-points in general, the probability of the aforementioned meeting, p_{meet} varies between 1% and 6%, for locations with 2 lanes in opposite directions, and depending on the traffic volume of the ATM-point under consideration. In the case of locations with 4-lanes – two lanes/direction, the traffic volume is typically higher and the meeting probability between lanes 1 and 4 varies between 28% and 39%. In locations with four lanes, the lorry traffic takes place mainly on lanes 1 and 4. The probability of meeting between the first and third line (fast lane) varies between 1% and 4%. Consequently, the overtaking probability between lanes 1 and 2 and between lanes 3 and 4 lies between 2% and 6%.

The analysis of data shows that the distance between the vehicle in the first lane and the meeting or overtaking vehicle is distributed according to uniform distribution (with parameters 0;300).

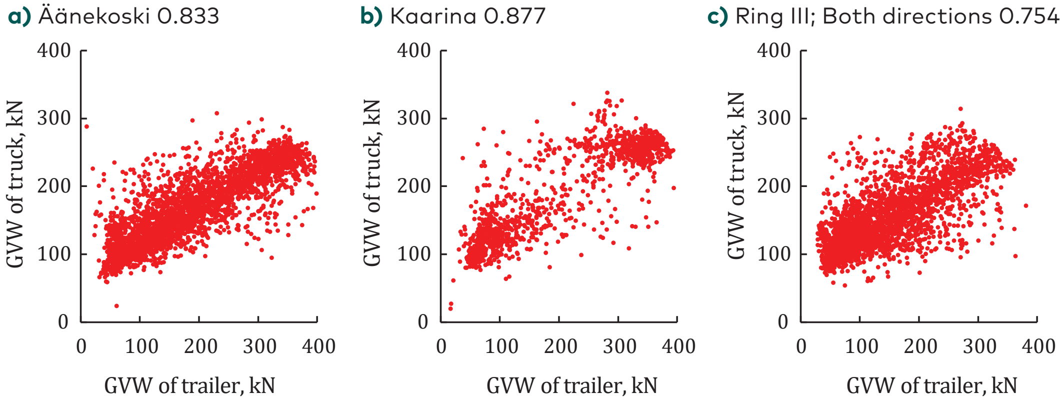


Figure 1. The correlation between truck and trailer for lorries with full trailer

The correlation between the gross weight of a lorry and trailer is assumed to be in unity in the simulation for simplicity. The assumption is verified later by analysing the axle weights of lorries with a full trailer in BWIM-monitoring data. In Figure 4, the GVW of the truck is plotted against the GVW of the trailer. It showed that the average correlation of weights of trucks and full trailers was 0.801, with data collected from four BWIM-monitoring points.

2.3. Predictive model for increased axle loads

The heaviest allowed axle and gross-vehicle weights were increased in legislation in 2013. The renewal cycle of road transport vehicles is several years, so it takes time to see the effects of the legislation change on the traffic load through monitoring. The data collected in AMS and used in the simulation are before the legislation change. The need of prediction of the effects of legislation change was evident to have adequate update for traffic loads. In a simulation, the effects of legislative change on axle weights are estimated according to a predictive model in this study.

The distributions of axle, tandem and tridem weights are modified by a factor depending on the shape of distribution, more precisely the location of the second mode, which corresponds to the mode of axle weights of loaded vehicles. The assumption is that the change in legislation has a full effect on the second mode and a less significant effect on values below that.

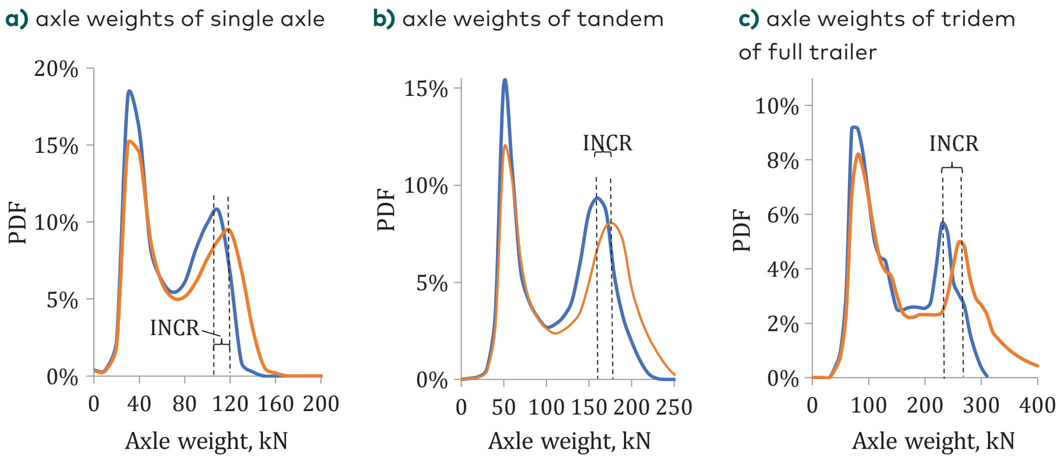


Figure 2. Observed distributions (blue) and predictive model (red)

The shift of distributions is made with a coordinate transform by using the equation:

$$F' = F\left(1 + INCR\frac{F}{F_{2.\text{mode}}}\right), \tag{1}$$

where F – original axle weight class, kN;
F' – estimated axle weight class after legislation change, kN;
$INCR$ – according to Table 2, %;
$F_{2.\text{mode}}$ – location of 2nd mode, kN.

In Figure 2, the estimation of the effect of legislation change on different axle groups is shown. The applied estimation model for shifting the second mode of distribution not only causes an increase in the mean value but also extends the right tail of the second mode.

2.4. Simulation of traffic flow

Convoys of lorries

The data used in the generation of traffic loads are based on ATM and AMS recordings. These two separate studies have records for over a year, which means that the traffic irregularities and variations during the day need to be modelled. The convoys of lorries (extracted from data) are considered to be loading events. The concept of convoys of lorries

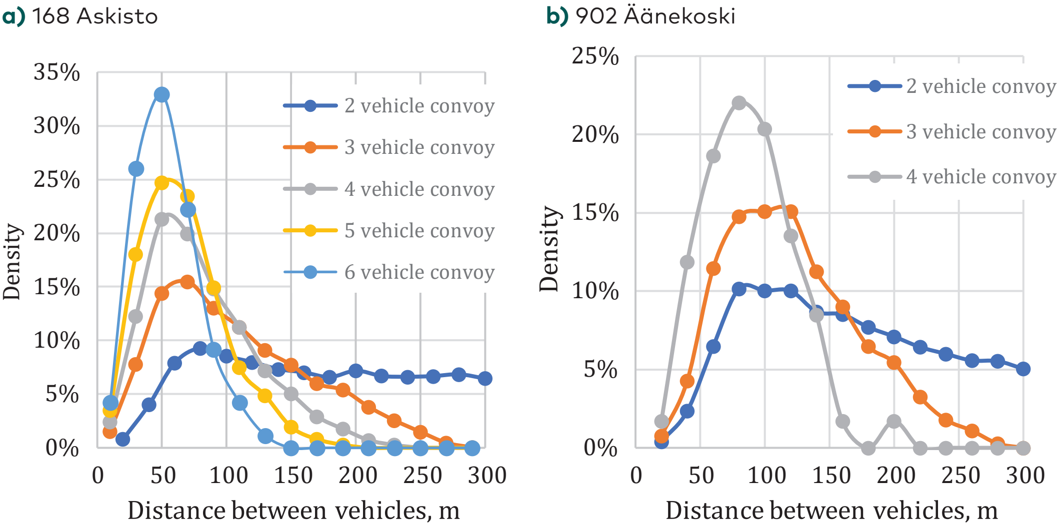


Figure 3. Distribution of intervehicle distance in convoys ($d_{c1,2}$ in Figure 9) in ATM points

in free-flowing traffic is implemented in ATM-data processing and the simulation to take account of the variability of lorry traffic density during the day. The convoys of lorries represent the peaks of lorry traffic in which the lorry traffic is denser (in certain length) than on average.

The intervehicle distances in convoys in the simulation are generated by using the distributions shown in Figure 5. For ATM-points with a significant amount of heavy traffic (road class 1), there are usually recordings of convoy lengths of up to six vehicles. In Figure 3b, which is collected on ATM-point 902 on road class 2, there were only a few observations of convoys with more than four vehicles.

The composition of free-flowing traffic is made by creating a single lorry or convoy of lorries according to the distribution presented in Figure 5. The distances between lorries in a convoy are determined according to distributions shown in Figure 3.

Loading events for the 1st lane

The generation of a traffic flow is done by the generation of a number of convoys to represent the daily loading events of the 1st lane of the bridge, so that the convoy of 1 to 6 vehicles represent a loading event. The convoys are generated according to a distribution of the convoy length and the intervehicle distance in convoys. The total number of vehicles in convoys equals a daily number of lorries at a corresponding monitoring point.

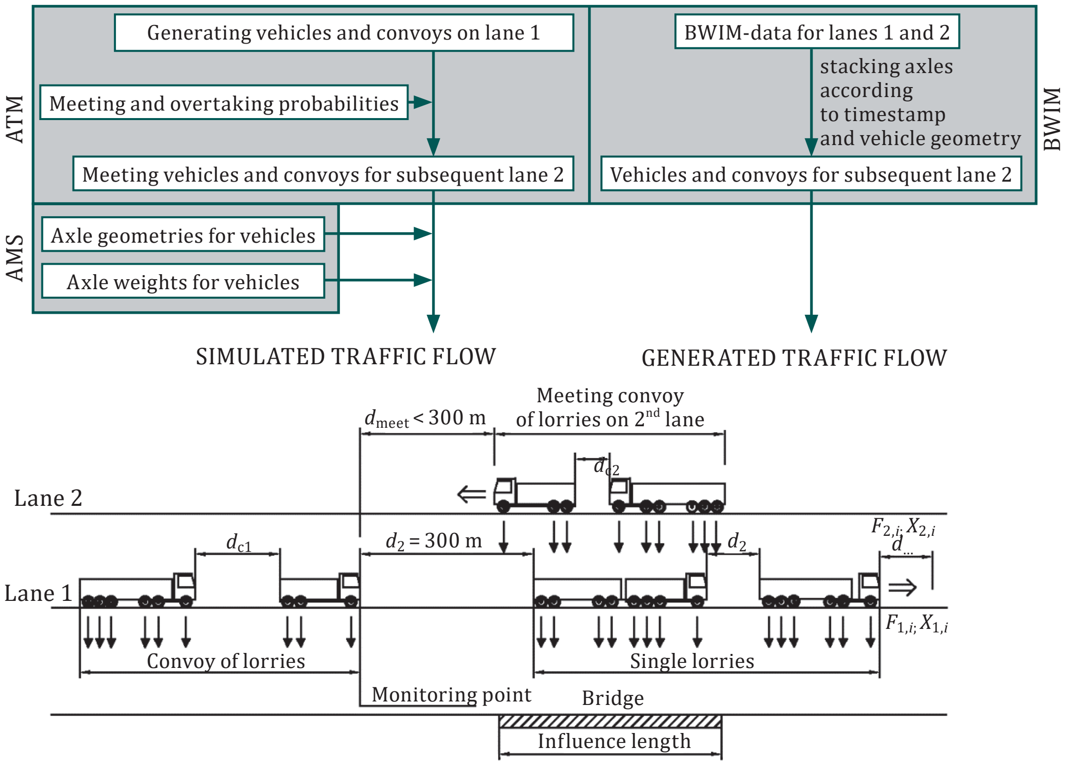
In the calculation, one long queue of point forces represents the daily traffic per lane. The distance between two subsequent loading events (single lorries, or convoys) is 300 m. This is done for calculation purposes to separate the loading events from each other while the 1-day traffic is generated and driven over the influence line. The intervehicle distances of lorries in convoys is generated based on separate data (see Figure 3). In the simulation, 100 days of traffic are simulated for each point and 1-day maximums are recorded.

Traffic for 2nd and subsequent lanes, loading events for a bridge

The load events of a multilane bridge consist of events: lorry on lane 1 or lorries on lanes 1 and 2 etc. The number of lorries and convoys for second and subsequent lanes is determined by using the probability of meeting or overtaking. The probabilities of meeting and overtaking related to event “load occurring at monitoring point” are extracted from ATM-data. The event “meeting” or “overtake” does not necessarily mean that the vehicles occur on the bridge influence length at the same time – unless the influence length is 300 meters, but, based on extracted information, it is possible to take account of the occurrence probability of this phenomenon and generate the load event simulating realistic load effect for combined lanes.

Traffic load modelling

Each generated lorry, whether it is part of a convoy or single, has axle geometry and masses generated according to axle mass surveys. For calculation purposes, the axles are converted to point loads, which are moved across the influence lines stepwise.



Note: d_{meet} – random distance of generated meeting vehicle on lane 2 (0 m < d_{meet} < 300 m);
$d_{c1,2,...,n}$ – intervehicle distance in convoy (5 m < $d_{c1,2...,n}$ < 300 m), see Figure 3;
d_2 – intervehicle distance or distance between convoys (constant 300 m).

Figure 4. An example of the generation of random traffic based on ATM-recordings and AMS and extracting data from BWIM-measurements for real traffic

Modelling of congestion

The presented method for modelling traffic applies and is based on monitoring records of free flowing traffic. However, the critical loading events for longer spans are caused by congested traffic. The characteristics of traffic congestion vary according to the topology of the traffic environment and are, therefore, highly site specific. Due to the shortage of reasonable recorded data of congested traffic situations in Finland, the congested traffic is assumed as simply and general as possible with a bumper-to-bumper model to be applied to the load model calibration in general. In studies (Buckland et al., n.d., Ivy et al., 1954), it is determined that this assumption is valid on bridge spans up to 200 meters. The load model of Eurocode (Eurocode 1: Actions on Structures. Part 2: Traffic Loads on Bridges. CEN; 2003, 2003) is based on a total jam situation with 100% of lorries in the slow lane (OBrien, Lipari, et al., 2015). In this study, only the model of lorry headways is affected in congestion due to the occurrence of cars between lorries, which is a more realistic situation in Finland.

The intervehicle distance between lorries is generated by a geometrical distribution of probability of i number of cars between lorries with p percentage of total traffic in Equation (2).

$$P(i) = (1-p)^{(i-1)}\, p \tag{2}$$

The maximum number of cars between lorries is assumed to be 50. The empirical distribution of the length of cars is based on ATM-data with median of 3.7 m and standard deviation 0.4 m. The car headway in congestion is assumed 1 m.

2.5. Traffic flow based on BWIM results

The collected BWIM-data are processed for each lane to create daily traffic (set of daily axles) on each one. The sets of daily axles (i.e., daily traffic) are moved stepwise across the influence lines and the traffic load effects are recorded. The method is the same as done with simulated traffic, but, in this case, the daily axles of real traffic (BWIM-records) are used. The total number of influence lines is 45. In this paper, the focus is on 15 of the most significant influence lines: Total load on length, bending moment on mid-span of simple beam and bending moment on support of two-spanned beam, which are often found to govern in the load model calibration (Connor et al., 2005).

3. Simulation results and follow-up study

3.1. AMS and BWIM data comparison

The data collected with AMS and BWIM contain information of lorry types and axle masses. The comparison of gross vehicle weights and distribution of lorry types is presented in Figures 5. In Figure 1, it can be noticed that gross vehicle weights collected in AMS are higher in comparison with those achieved in BWIM. The variation of distribution of lorry types can be noticed in Figure 5, which shows that the proportion of single lorries is much higher on monitoring points located on Ring roads in comparison with highway results in Äänekoski or the overall results of AMS, collected from multiple highways.

The variation of results between monitoring points exists and, therefore, comparisons of the ATM point and BWIM point near each other are relevant.

Table 6. Comparison of traffic intensity and GVW's of AMS+ATM and BWIM results

Method	Location	N / direction	*M*, kN	σ, kN
ATM	Äänekoski	398	337	152
	Ring III	1995	247	143
BWIM	Äänekoski	374	298	162
	Ring III E/W	1887/1577	193/242	115/147

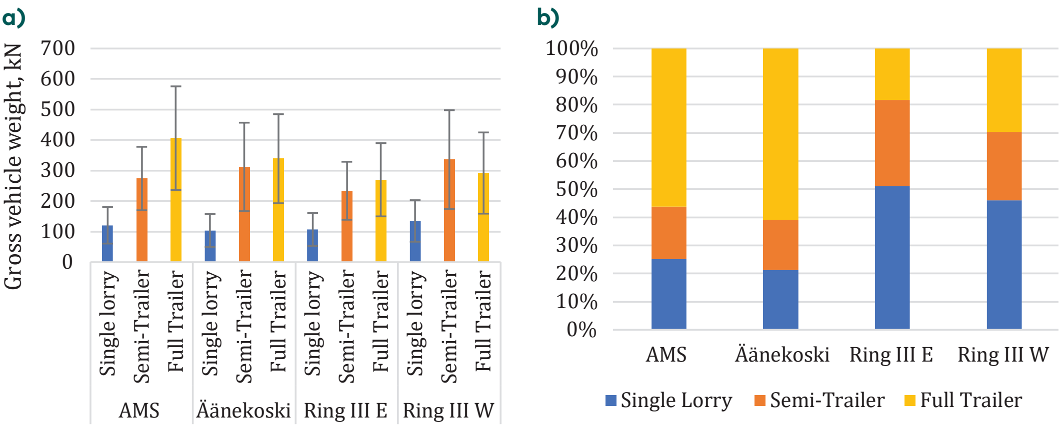


Figure 5. a) Average and deviation of gross vehicle weights of lorry traffic in AMS and in three different BWIM locations; b) corresponding proportions of different kind of lorries based on comparison of the 2014 data

The data collected in BWIM-monitoring consist of 7 days. The value of the gross vehicle weight from combined AMS-data is achieved with a simulation by generating a sample (n = 10 000) of independent lorries. In the simulation, the value of the gross vehicle weight is 13% heavier in comparison with the monitored value of BWIM 2014.

The simulation with AMS+ATM data produces the value of the gross vehicle weight 26% heavier in comparison with the Eastbound lane monitored value. In Westbound lane, the monitored gross vehicle weights seems to match the simulated values well. For some

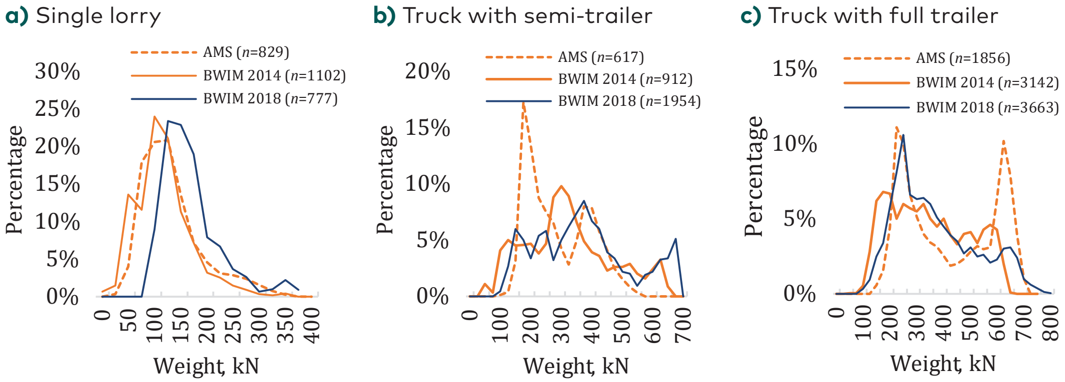


Figure 6. The distributions of gross vehicle weights of heavy vehicles in different categories

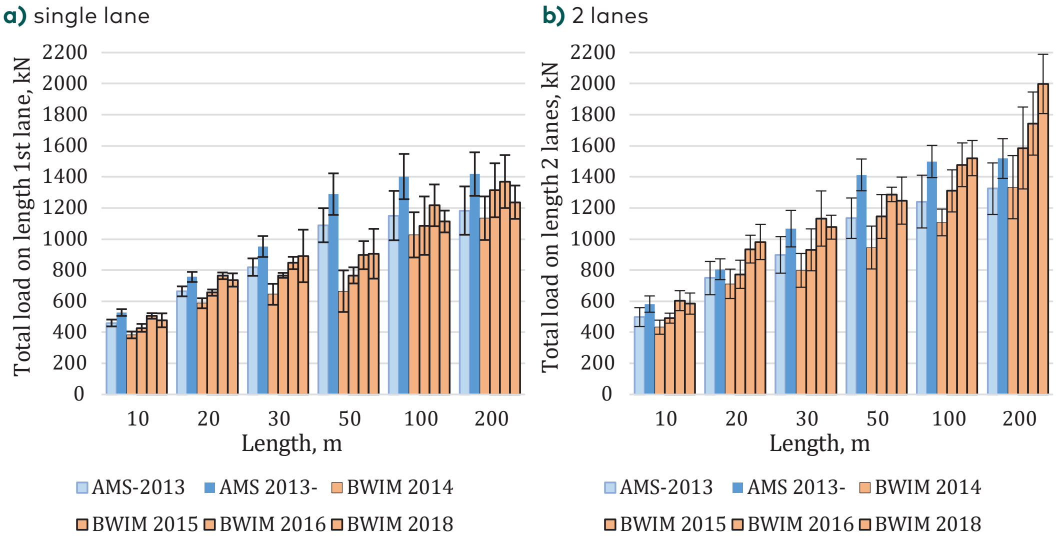


Figure 7. Simulation results vs. BWIM results of total load on influence length

geographical reason, the monitored lorry traffic is significantly heavier on Westbound lane in comparison with the monitored value on Eastbound lane of Ring III.

In Figure 6, the distributions from AMS (solid) line for different vehicle classes are presented against measurements BWIM2014 and 2018. In every class, the distribution is shifted towards right showing increase in GVW from 2014 to 2018.

The simulation results of load on total length in Figure 7 give an overview of the simulated effect of legislation change (light blue and dark blue columns) and monitored change according to processed BWIM-data. The increasing trend can be observed in both: simulated results (with prediction) and 2014 to 2018 in BWIM results. For 2-lane traffic, the monitored results exceeded the simulated ones achieved with a predictive model. The error bars presented in Figure 7 show the standard deviation of daily extreme of total traffic load. The average coefficient of variation is typically smaller for single lane, in 10–30 m it is 5%, while for 2 lanes the average COV is 12%. In 50–200 m, the COV increases to 10–15%. In BWIM-results, the same behaviour is observed for shorter lengths: the average COV is 6% and for longer lengts it is 12%. In case of two lanes in BWIM, the average COV is 12% and the difference in short and long influence lengths cannot be distinguished.

3.2. Askisto – Ring III Location

The comparison is made by using the simulated traffic in ATM-point 168 – Askisto and BWIM-point RING III East, in which the traffic in lanes 1 and 2 are in same direction. The comparison of the mean values of 1-day extremes is made for each influence line. The χ-factor for selected influence lines is presented in the following figures to show conservativeness of simulation results in comparison with the monitored ones for different years.

$$\chi_i = \frac{\mu_{\mathrm{SIM.AMS.1day.}i}}{\mu_{\mathrm{BWIM.1day.}i}} \tag{3}$$

The χ-factor for selected influence lines is presented in Figure 8. The calculation of χ-factor is done by dividing the mean value of 1-day extremes of simulation by the mean value of one day extremes based on BWIM according to Equation (3). The value $\chi > 1.0$ indicates that the simulation is conservative in comparison with the monitored BWIM value.

In Figures 8 and 9, the χ-values show that the results achieved with the simulation are the most conservative values in comparison with the monitored results in 2014. Especially the simulations made with

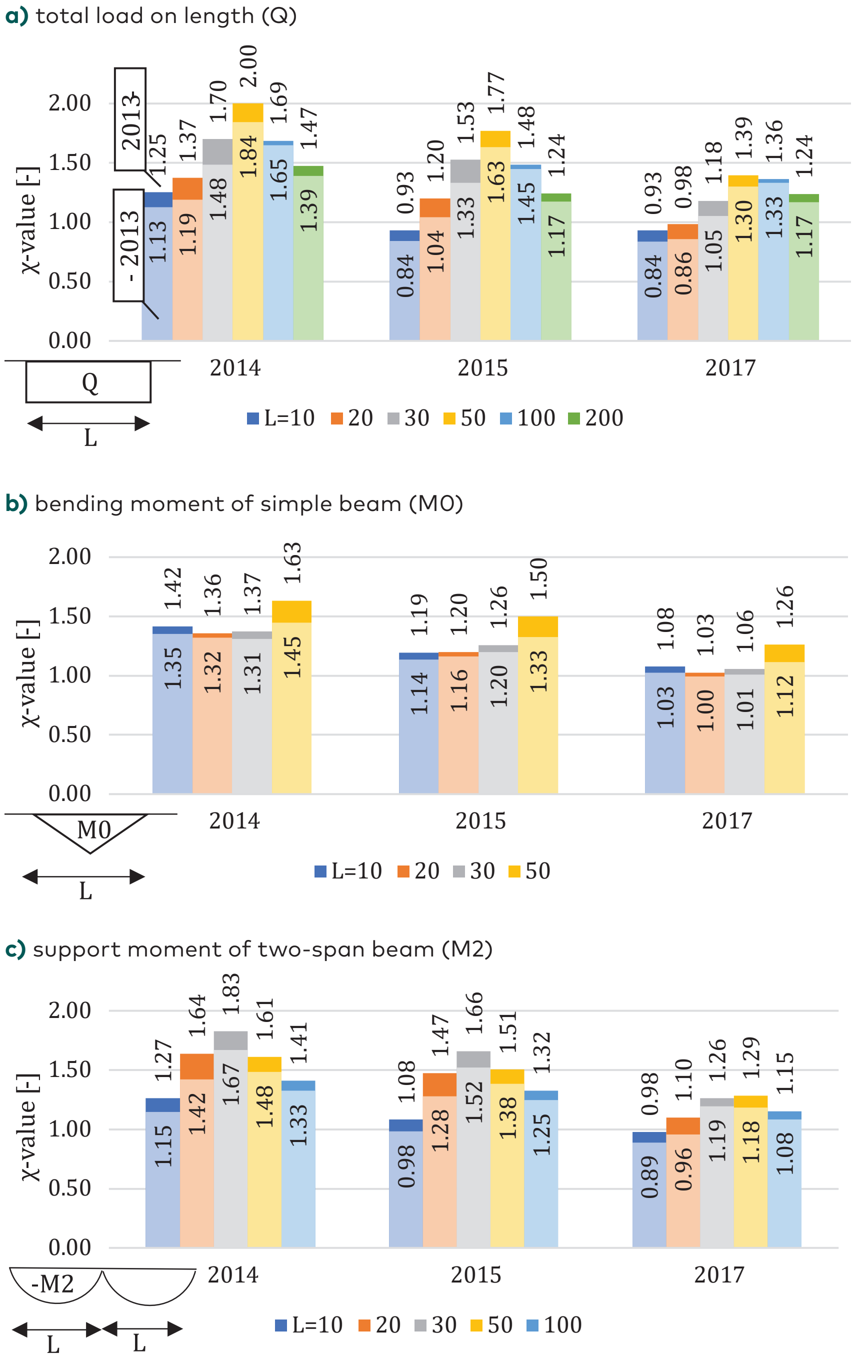


Figure 8. χ-factors for total load on length, bending moment at midpoint of single span, bending moment on middle support of 2-span beam in Askisto

a predicted increase in axle loads (marked as “2013-” and bold colour in Figure 8a are conservative. The figures show that the χ-value is decreasing with the years, in every influence line. This means that the conservativeness of the prediction model in the simulation is decreasing, i.e., axle loads and GVWs in roads are increasing as was predicted in 2014.

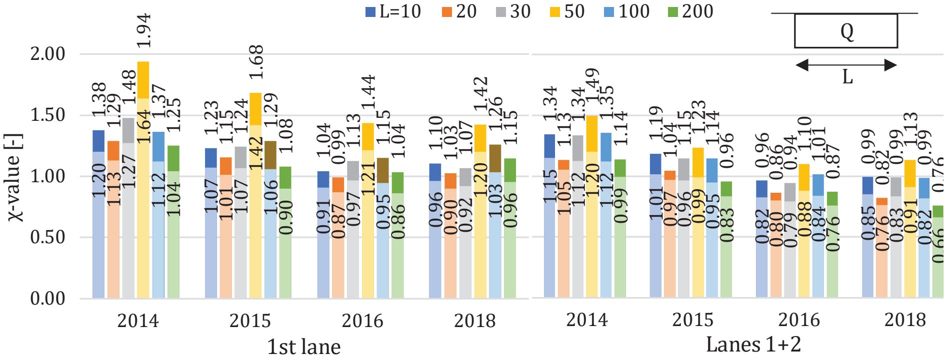
The lowest χ-values occur generally on the shortest span lengths in 2017, which shows an increasing trend in GVWs and axle loads of single vehicles. The difference between the extreme values of the first lane and combined lanes 1+2 is a couple of percentages due to the low number of lorries on the second lane in the same direction, which means that the effect of the second lane on influence extreme value is negligible.

3.3. Äänekoski location

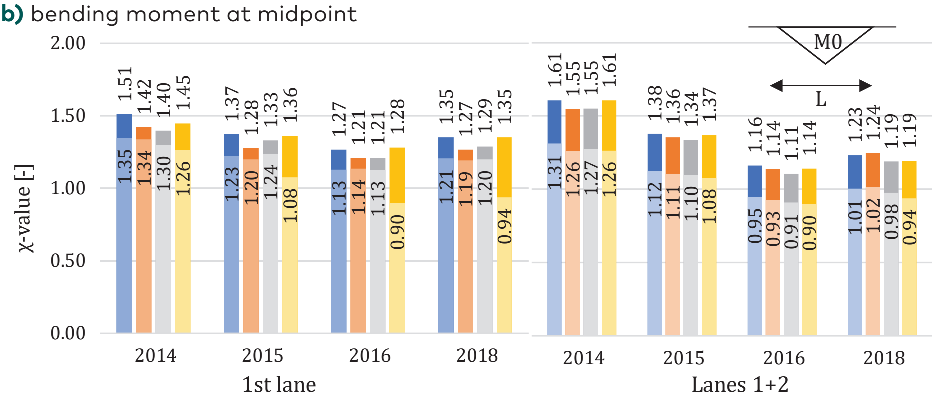
The comparison is made by using the simulated traffic in ATM-point 902 (Äänekoski). The χ-values for Äänekoski location are calculated in Figure 8, which shows the same trend, as in Askisto (Figure 9). The conservativeness of simulation model decreases in time. At this monitoring point, the traffic in the second lane flows in the opposite direction in comparison with the first lane. The number of lorries is also high in the second lane, whereas it is low at the Ring III-Askisto point.

The high number of lorries on both lanes causes a higher load effect on the bridge in comparison with a single lane due to higher probability of occurrence of vehicles on both lanes. The conservativeness of the model decreases when the combined effect of lanes 1+2 increases over time. The part of the effect can be explained by the increase in the number of lorries and the increased probability of a presence of multiple lorries on the lanes of the bridge, especially in longer lengths. This causes the low values of χ in longer influence lengths.

a) total load on length



b) bending moment at midpoint



c) bending moment on middle support of 2-span beam for 1st lane and combined effect of lanes 1+2

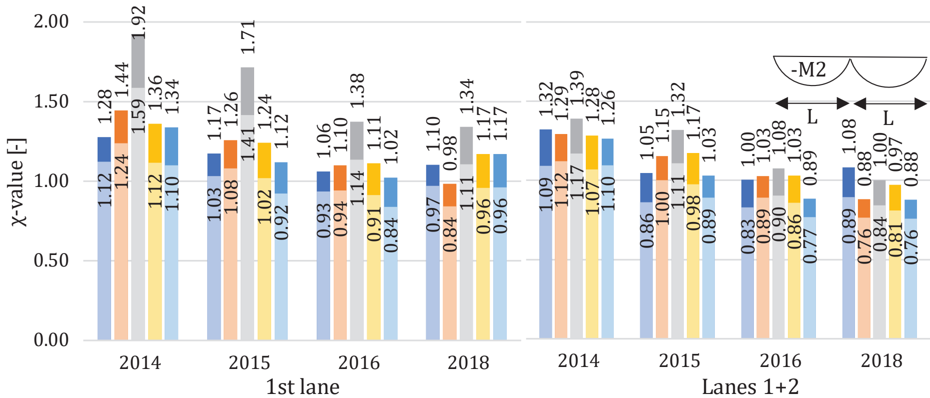


Figure 9. χ-factors for a) total load on length; b) bending moment at midpoint; c) bending moment on middle support of 2-span beam for 1st lane and combined effect of lanes 1+2, in Äänekoski

4. Interpretation of results: Extrapolation of characteristic traffic load effect

The daily extremes of traffic load effects are collected for each influence line and location. The extreme value distribution of daily maxima is done by using block maxima method with a block length of one day. This method is found to be the most adequate for bridge traffic loading studies (OBrien, Schmidt, et al., 2015). The distribution of daily extremes is assumed to follow type I extreme value distribution (Gumbel) in reference (ENV 1991-3 Traffic Loads on Bridges Background and Notes, 1994). In current example simulations (total load on length), Figure 9 shows that the GEV with $\xi < 0$ fits better on distribution tail. The trend of tail is curving slightly upwards referring to compliance to Weibull distribution. The characteristic value of traffic load effect is set to correspond to a load with a T = 1000-year return period.

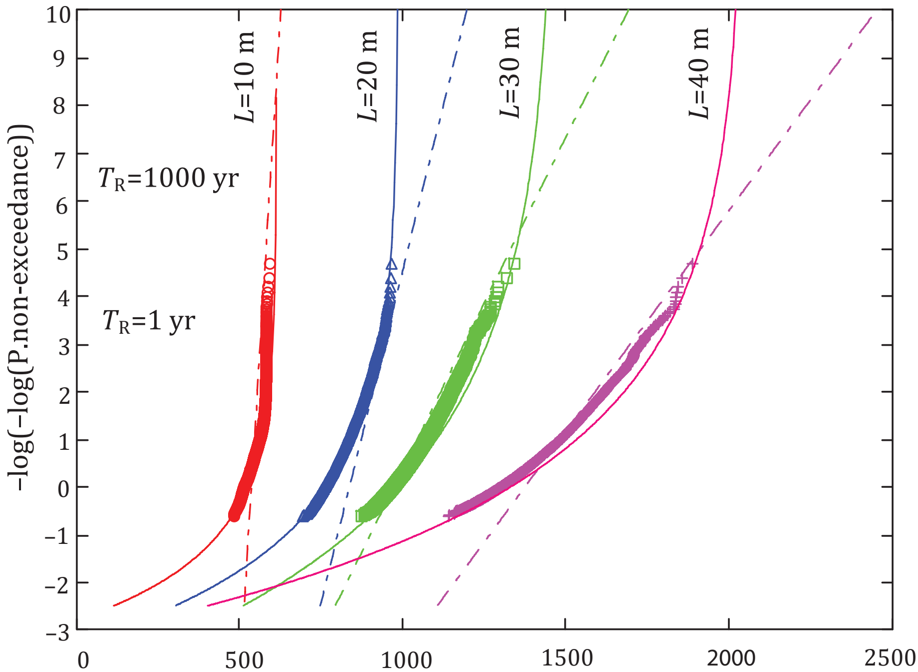


Figure 10. Simulated daily load effects and predicted extreme values for load effects for single lane V1

The relation between probability of non-exceedance of certain load level F(z) and return period is given:

$$T(z)=\frac{1}{1-F(z)}. \tag{4}$$

The y-axis ordinate for standard extremal variate (SEV) in Figure 9 can be calculated as follows:

$$SEV(z)=-\log\left[-\log\left(F(z)\right)\right]. \tag{5}$$

To achieve a value for a load effect with a return period of 1000 years, one must observe a certain fractile of the tail of cumulative extreme value distribution of daily maximums. A year traffic is usually assumed to consist of 250 weekdays, with the weekends and holidays being ignored (OBrien, Schmidt, et al., 2015). However, the average number of lorries in simulated locations is synthetic daily averages without a separation of weekends and weekdays; the correct value for extrapolation in this case is 365 days/year (Zhou et al., 2018). If weekends and weekdays were separated by data, the fractile would be smaller while the mean value of daily extreme was higher. In the case of free flowing traffic, the corresponding fractile for a 1000 year return period is $1 - 1/(3.65 \times 10^5) = 0.999997191$, which corresponds to $SEV = 5.925$.

In the case of congested traffic, the modelled traffic with a block length of one day consists of the average number of lorries/day. An estimation for the length of the traffic congestion is 2 hours/day, the daily number of lorries simulates actual congestions of 12 days. This means that the observed fractile of the extreme value distribution of the load effects caused by congested traffic is $1 - 1/(365 \times 10^5) \times (2/24) = 0.9999671233$.

4.1. Calibration of load model LM 1

The selected values for axle loads and UDL for the load model are made based on calibrating the load effects of the load model with simulation values to make the 'fit' as good as possible as shown in Figure 11. The tolerance of 5% is allowed for simulated values to exceed the effects of the load model on the first lane to achieve a reasonable load effect and to avoid excessive loading for the first lane of LM1 as can be seen in Figure 11 (dashed green and red lines exceed the dashed blue line). The selection is justified because, in practice, the traffic lanes are wider than 3 m which is the width of load lanes in LM1. The case in which the only lane of the bridge is covered by only one LM1 lane barely exists. For influence line of total load on length the congested traffic of lanes 1+2

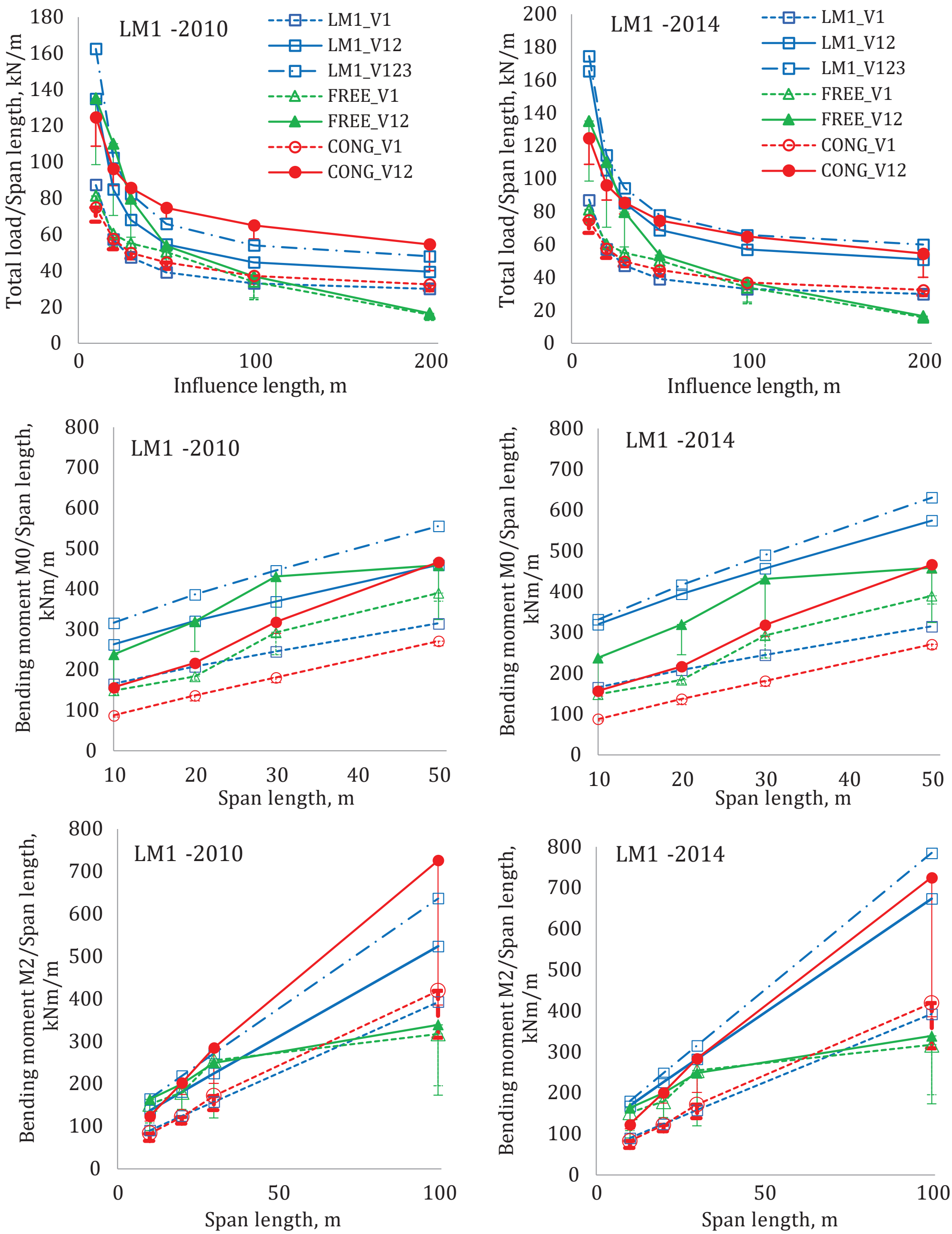


Figure 11. The selection of LM1 and calculated characteristic value of selected influence lines for free flowing traffic V1 and V12 and congested traffic V1 and V12

(marked red continuous) is the most determinate effect, exceeding the values of LM1-2010 especially with lengths longer than 50 m.

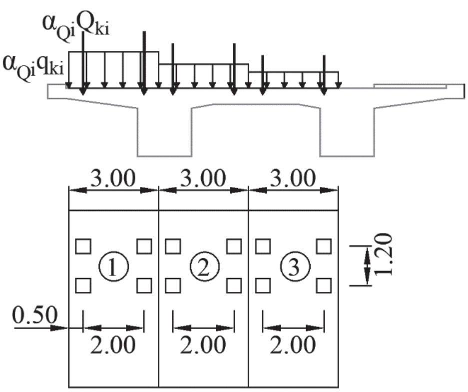
The AMS data used in the simulation are static, achieved with a stop and scale method and, therefore, do not include any dynamic component. Because the load model LM 1 includes dynamic effects of traffic load, a selection of the dynamic factor (DMF) should be made. For comparison purposes, it is convenient to select an equal model for a dynamic factor as in the original calibration of LM1 in (ENV 1991-3 Traffic Loads on Bridges Background and Notes, 1994). For the results of congested traffic, the dynamic factor of 1.0 is selected.

Based on results of all of the influence lines, the suitable values for alpha factors for load model LM1 in Figure 12 are chosen and the effects are plotted in Figure 11. The selection for LM1 axles was 2 × 300 kN + 2 × 300 kN + 0 kN. For LM1 UDL: 9 kPa; 6 kPa and 3 kPa for lanes 1, 2 and 3, respectively.

4.2. Sensitivity analysis

In the simulation, the greatest effect on results is caused by the distribution of gross vehicle weights and axle masses of lorry traffic. The increase in vehicle weights in input data has a direct impact on results. The traffic intensity has a minor effect on simulation results because only extreme values of a certain period are of interest. The increase in traffic intensity must be significant (multiple) to cause an increasing effect on the resulting extremes, which is also found in Connor et al. (2005).

The selection of a reference length of 300 m to be the maximum distance between events (lorries or convoys) is made to reduce the



	LM1 -2010		LM1 -2014	
	$\alpha_{Qi}Q_{ki}$, kN	$\alpha_{Qi}q_{ki}$, kN/m^2	$\alpha_{Qi}Q_{ki}$, kN	$\alpha_{Qi}q_{ki}$, kN/m^2
Lane 1	2 × 300	9	2 × 300	9
Lane 2	2 × 200	2.5	2 × 300	6
Lane 3	2 × 100	2.5	–	3
Other	–	2.5	–	3
Outside area	–	2.5	–	3

Figure 12. The selection of Load Model LM1

simulation time (i.e., shorten the daily traffic in calculation). The selection of the refence distance does not affect the simulation results as it affects the input data itself, if the reference length is increased, whilst also the meeting probability of two events is increased. Still, the probability of the occurrence of 2 events on the influence length remains the same.

5. Discussion

A method of estimation of future loads of lorry traffic due to legislation change is presented in this paper. A simple approach based on the change in allowed axle loads can be used to predict the change in probability distributions of axle loads in the case of a simulation of traffic load effects. The analysis (Figures 8 and 9) shows that the transfer period for legislation to take the full increasing effect on actual axle and gross vehicle weights seems to be in an order of 4 to 5 years during which the conservativeness of prediction model decreases significantly. This proved that the predictive model and methodology of a simple approach functioned rather accurately by increasing statistical distributions based on distribution shifting according to legislation change.

In Figures 8 and 9, the peak of conservativeness is noticed on medium spans with length of 50 m, while the values are lower for other lengths. This shows that the simulation model overestimates the GVW of the longer single lorries consisting of multiple parts. The assumed full correlation between truck and trailer axles resulted in the conservative results of model. In the same figures, the increase in axle and bogie loads more than predicted can be noticed while the conservativeness of simulation drops below 1.0 with shorter spans, which means that the monitored load effect on spans exceeds the simulated one.

Within short influence lengths, the modelling of a statistical distribution of gross-vehicle-weights of single vehicles is a rather good method for the estimation of total load on length. For longer influence lengths, the variability of traffic density should be taken into account as multiple vehicle presence. In this paper, the traffic data are used to construct convoys of lorries for a traffic simulation to model this phenomenon. Also the variation of daily extremes increases due to multiple vehicle presence, this applies to both cases: multiple vehicles on a single lane in long influence length and shorter length with multiple lanes. The overall weight of convoys in a simulation shows about a 10% difference to monitored ones when longer influence lines for overall weights are compared in Figures 8a and 9a. The bias is caused by the above mentioned difference between AMS, which is used as general input for simulation, and BWIM records of single vehicles.

It is obvious that the data collected in the AMS do not represent the traffic load effects and distributions of gross vehicle weights on all roads in Finland. The input data based on an AMS are collected all around the road network of Finland. It does not represent accurately any location, but represents the average heavy traffic composition. The variation in traffic exists, for example, due to the geography of the manufacturing industry, retail and cities. In certain locations, the simulation is conservative. This can be seen in comparison of monitored values of Ring III Eastbound and Ring III Westbound 1-day extremes, in which the average difference is 13%. This means that variations due to the above mentioned reasons really exist.

The recalibration from LM1-2010 to LM1-2014 resulted in more concentrated load distribution in transversal direction shifting more load on the first lane, while load in the 3rd lane decreased. This is a direct result due to an increase in the allowed GVWs and axle loads, which led to single vehicle presence or multiple vehicle presence to be the most determinate loading event for bridge with multiple lanes. If only one LM1 lane is considered against one simulated lane, the increase in load model should have been even greater to cover the effects of simulated traffic. However, the case in which only one LM1 lane fits on bridge deck is rare, including cases in which there is only one real lane. Therefore, exceedance shown in Figure 10 (dashed lines) is justified. Also a bridge with two lanes typically has enough width to cover three LM1 lanes instead of two.

The results and simulation model presented in this paper can be used for the determination of traffic load values for different return periods and structures. The calibration of load models for different purposes is also possible, which is shown as a proposal of updated LM1 due to change of legislation. For example, the distributions of live load effects can be determined for a reliability analysis of existing bridges for a specified road class of bridge site. The further research is to study realistic traffic congestions for different sites in Finland to achieve a more sophisticated model for congested traffic loads.

Conclusions

The predictive model for increased traffic load showed that the load model LM1-2010 was not large enough to cover the demands of increased vehicular loads after 2013 and, therefore, the used design load underestimated the traffic load effects which were realized after legislation change. With BWIM monitoring, these effects were verified. Based on this conclusion, there may be a need to assess the load bearing capacity of bridges designed with load models older than LM1-2014.

The presented calibration of a predictive simulation model based on the change of allowed axle loads and gross vehicle weights can be used in the estimation of the evolution in traffic load effects and calibration of load models in case of future changes of legislation. The increase in allowed axle loads has a direct impact on the traffic induced forces on structures. According to follow-up study, the transfer period for a full effect is more than three years to change in legislation to take the full effect.

The forecast model performed rather well for prediction of increase in traffic load effects due to legislation change and, therefore, the measures taken to recalibrate LM1 in year 2013 based on the estimation seemed to be suitable for increased allowed axle and gross vehicle weights. To construct the model for future calibrations of traffic load model, the generalization of traffic needs to be done due to large variation in traffic composition and traffic load effects on different locations.

The modelling of convoys of lorries as loading events simulates the variability in traffic density during the day if only average data of traffic are available without daily and hourly variations. The modelling of convoys and lorry headways is essential for longer influence lengths as multiple vehicle presence is determinate in terms of total load and increased variation. Also modelling of convoys is an effective way to achieve an adequate estimate for the extreme values of traffic induced load effects.

Data availability

Traffic monitoring data used during the study were provided by a third party. ATM recordings were provided by Destia Ltd and the data from BWIM-monitoring by Trafikia Ab. Direct requests for these materials may be made to the provider as indicated in the Acknowledgements.

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