TRAFFIC LOAD MODELS FOR SHORT SPAN ROAD BRIDGES IN LATVIA

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Abstract. Bridges are structures that are designed for a service life up to hundred years. However the actual traffic load models significantly differ from the characteristic load models used in the design. Analysing the design codes used in Latvia for past twenty years it was found that the design loads on the bridges have doubled since the codes were approved. Therefore the use of the actual traffic load models to assess the load carrying capacity of the in-service bridges can significantly save the maintenance cost. In the past traffic actions had an attribute of a great uncertainty; however with the introduction of Weight-In-Motion systems it is possible to collect vehicle information without interfering with the traffic flow. This includes data such as - number of axles, vehicle wheelbase, speed and axle loads which altogether shapes the picture of actual loading range on the roads and bridges. The collected Weight-In-Motion data analysis was performed to obtain load distribution diagrams, determine heaviest axel disposition, traffic speed and intensity values. This paper presents research done to develop traffic load models and determine values of the Eurocode load model LM1 calibration factor alpha for bridges with a span length up to 30 meters, considering the characteristic loads on Latvian roads and bridges.

Keywords. Bridge; Load; Traffic; Load model; Weigh-in-motion; Vehicle load; Statistics.

INTRODUCTION

Transport flow in Europe is dominated by the road transport and serves all Europeans on a daily basis. Therefore, one of the EU's research priorities has become the research of road infrastructure network enhancement techniques (EK, 2008). Compared with previous years, new roads and bridges are being built less often, hence greater investment in maintaining the functioning of existing infrastructure is needed, moreover, to insure appropriate safety standard implementation.

Over the past years the number of vehicles on EU roads has increased. This indicates continued growth of the traffic load and its composition changes, and has to be taken into account for both the design of the new bridges and evaluating existing ones.

Currently there are 936 bridges on the Latvian national road network, of which: 880 are reinforced concrete bridges, 16 are bridges of stone and brick, 33 are steel bridges and there are seven timber bridges. Most of the bridges have been built after the Second World War. Regular bridge inspections have shown that about 60% of the bridges in service have varying degrees of damage that affects their bridge load-carrying capacity. Bridge damage can be caused by deterioration of the structure, poor quality of materials and construction, lack of maintenance, increasing traffic loads and environmental pollution.

Considering the current financial situation and with the limited amount of money dedicated to the necessary bridge reconstruction or repair, it is important to clarify the actual traffic load effect on the bridge structure, to evaluate its structural capacity and determine the limits within which the existing bridge structures are safe to operate.

Until now determination of the traffic loads was a long and time-consuming process during which the road traffic was counted and vehicles weighed in specified locations. The obtained data were then used for traffic load forecasting. This collected data was not always sufficient and accurate; however according to them normative load models of the bridge design were developed.

In recent years new methods have been developed which with reasonable accuracy allow determination of the actual traffic load, traffic composition and intensity on the existing bridges. One of such methods is „weight in motion "(WIM), which will be used in this study. This method uses a measurement system, which allows measurement of gross weight, axle load, axle number and speed of each vehicle in motion.

Latvia started to use normative load models for bridge design in 1900. During the past century, load models changed more than six times, and each time vehicles gross weight has been increased, thus every load model is taken into account in the design of new bridges (Gailis, 2002) (Ciguļskij, 1911)

(Vinogradski, D.J., Rudenko, J.D., Škuratovski, A.A., 1983) (SN_200-62, 1962) (SNIP_2.05.03-84, 1985) (LVS_EN_1991-2, 2003). With increasing knowledge of structural behaviour design calculation methods have become more and more precise. Therefore, it is possible to reassess bearing capacity of existing bridges by applying modern transport load models. Load models given in Eurocodes often give larger stresses than the original load model of an "old" bridges, therefore bearing capacity is evaluated as insufficient. Although the load-bearing capacity is not sufficient for the Eurocode load models, it is adequate for the actual traffic load.

1 TRAFFIC LOADS

Traffic load is one of the most complex variables that significantly affect the uncertainty of the bridge element assessment. Traffic load models in different national standards are very conservative and are intended primarily for the design of new structures. (Nowak A. S., Live load model for highway bridges, 1993) (Nowak A. S., Probabilistic basis for bridge design codes, 1989) (Nowak A. a., 1991) (Ricketts, 1997) (Laman, 1997) (Van_De_Lindt, 2004) (Vrouwenvelder, 1992) (Waarts, 1992) (Znidaric, 1995) Most of these models have been developed using a short time observation of heavy traffic flow on which long-term load effects are extrapolated.

Traffic load induced effects depend on many variables such as the vehicles weight, axle weight, axle spacing, speed, etc. In-service bridge carrying capacity assessment methods are based on the technical assessment and real-time traffic analysis of structures. Various studies show that the actual traffic load is up to 50% less than those in standards (OBrien & O'Connor, 2012). Due to traffic loads given in national standards, we could design a bridge with a large carrying capacity margin, which sometimes is not economically viable. By studying the regulatory load factor α value, it is found that it is largely dependent on both the bridge span length and width of the roadway and the road category.

As the composition of traffic and assessment of each country is different and cannot be used directly elsewhere, it is necessary to determine appropriate load models for Latvia using long-term WIM data.

Further analysis of historical and currently used traffic load models for bridges in Latvia and their load value increases was performed (Gailis, 2002) (Ciguļskij, 1911) (Vinogradski, D.J., Rudenko, J.D., Škuratovski, A.A., 1983) (SN_200-62, 1962) (SNIP_2.05.03-84, 1985) (LVS_EN_1991-2, 2003). It was found that vehicles used today, compared to those historically used, are longer, with a higher number of axles and the larger distance between them, so their effect on the load bearing construction of the bridge in many cases will be smaller as all axles cannot fit onto a small or mid-span bridge at the same time (Paeglitis & Paeglitis, Simple Classification Method for the Bridge Capacity Rating, 2010). Therefore, it is important to clarify typical traffic load patterns of Latvian road bridges and integrate them into the small-and medium-span bridges carrying capacity assessment of existing bridges.

2 DATA ANALYSIS

2.1 Data validation

Part of the WIM data had to be excluded from further processing due to low validity. It was done applying data filters using four criteria:

- The first criterion is the maximum permissible axle load, which was adopted equal to 40 tons.
- The second criterion is the total weight maximum of the vehicle, which is assumed equal to 300t.
- The third criterion requires a minimum total vehicle weight of 3.5 t. In this way only heavy vehicles are taken into account.
- The fourth criterion is the speed of the vehicle. Its limit is set at 150 km / h. It is more than the permitted speed limit. However, due to vehicle drivers reckless driving much of the heavy vehicles data would not be included

2.2 Data processing

The next step in data processing is establishment of the template file for each set of parameters. The first template file includes information on all of the axles weight distribution, the maximum axle weight distribution, distributed load distribution and gross vehicle weight distribution of 2,3,4,5,6, and > 6-axle vehicles. The second template file was created to evaluate determinative vehicle axis and total number of vehicles divided by the number of axles. The third, fourth, fifth, sixth and seventh template file is created similar to that described above, the only difference is number of axles, which, accordingly, are accepted 2, 3, 4, 5 or 6. In processing of the data, 46 files was created that contained information about 1 million vehicles. In each data file complete traffic information of 33 weeks was utilized creating in total 322 processing files. To illustrate the traffic load analysis methods see (**Fig. 1.**).

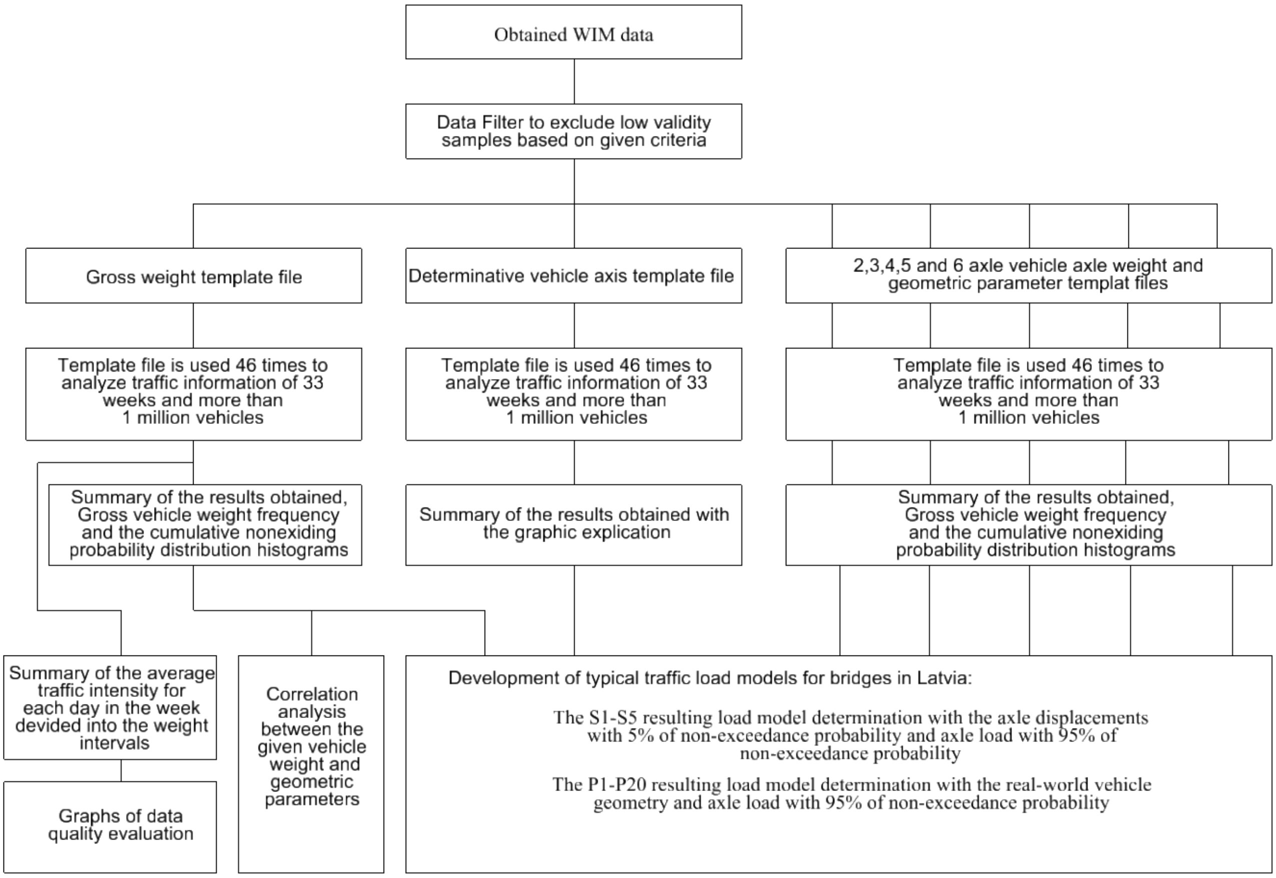

Fig. 1. Flowchart of traffic load analysis method

For the selection and representation of geometrical parameters the frequency and cumulative distributions histograms are widely used (Bailey, 1996). For histogram design, the following algorithm was used. The variable number n was determined for every measured value that reached one million, and range r depends from the measurements maximum and minimum values (Kronbergs, 1988). Both the number and size of variable classes in this research were determined according to necessary accuracy (Krastiņš, 1978). The total axle loads and maximum axle load distribution load class size was adopted - 0.2 t, and distributed load - 0.2 t / m, while vehicle gross weight distribution class size was equal to 1t. For individual 2, 3, 4, 5 or 6 axle vehicles weight and axle placement parameters were defined following class sizes: speed distribution - 5 km / h, vehicle length - 0.5m, axle load distribution - 1t, and axle separation distribution - 0.5m. When vehicle load models P1 - P20 were created a class size of distance between the axles was reduced to 0.25m.

2.3 The main mathematical equations

Absolute class frequencies n_j is calculated next by counting how many random elements are in each class interval (Krastiņš, 1978). To select and count the number of elements within each class of variables MS Excel function "COUNTIF" were used in. The relative class frequency f_j can be determined by dividing the absolute frequency of class N_j with the total number of elements in the sample n (1).

$$\sum_{1}^{n_c} f_j = 1 \tag{1}$$

The absolute class cumulative frequency is N_j. Variable class j is the total number of elements that fall into the classes from $N_i = 1$ to $Ni = j$ inclusive. The relative cumulative frequency of class F_j is obtained by dividing the absolute cumulative frequency of the class N_j and the total number of elements in the sample, N. If $j = n_c$, then $F_j = 1$, formula (2).

$$F_j = \frac{N_j}{N} \tag{2}$$

The resulting values are summarized in the table and are designed as based on the data table histogram.

In cases where it is practically impossible to calculate probability in the classical definition, the relative frequency calculated for a large number of attempts can be used instead (Kronbergs, 1988). This means that the greater the amount of collected data, the more accurately it describes the probability values. Based on the large amount of data used in this study it is assumed that the relative cumulative frequency graph values represent necessary probability.

2.4 WIM system accuracy and volume of data

For this study used WIM data were obtained from measuring equipment which was installed from year 2002 to 2008 on the motorway A4 (Baltezers - Saulkalne) between P5 and A6 (Riga - Daugavpils - Kraslava-Belarus border (Pāternieki)). The measuring equipment was located 500 meters before intersections in this roadway, thus providing free traffic conditions and a good data collection situation. In 2011 the measuring equipment was dismantled because the sensor was damaged by the traffic load.

Within six years WIM system collected data on more than 17,568,000 vehicles, about 244 000 vehicles a month. Initial processing of the data showed that the WIM sensor error in the first year was about 5% in the second year - 15% and in third year 25% (Rob Bushman, Andrew J. Pratt, 1998).

Data from year 2002 and 2003 were not used in this research because of its very fragmentary nature, but the 2005 - 2008 data was already of poor validity and were excluded from further processing. Therefore, this study was carried out by processing only data from year 2004 that consisted of 33 weeks of measurements. Total magnitude of vehicles in 2004 was 1 172 842. Of these, 449 218 vehicles weighed were less than 3.5 tons, but 663 101 vehicles weighed more than 3.5 tons. Data on 60 523 vehicles were incomplete and could not be used for further analysis. Statistical analysis of data showed that 861 165, or 79.82% are two-axle vehicles. The second largest group was the five-axle vehicles – 12.48%, and three-, four-and six-axle vehicles were only 6.25% of the total (Paeglitis & Paeglitis, Weight-in-Motion Data Analysis of Vehicle Loads of A6 Motorway in Latvia, 2012).

3 LATVIA-SPECIFIC ROAD TRAFFIC LOAD CHARACTERISTICS

Analysis of Gross vehicle weight showed that the largest proportion of vehicles on the roads are cars with a mass around 3.5 t, the second largest proportion of vehicles weigh around 37 tons, while the third - with a mass of 90 t (**Fig. 2.**). The maximum vehicle weight of 94-95t is determined with 95% probability, with the remaining 5% of vehicles with a mass of up to 300 tons occur very rarely and must receive special permits from authorities.

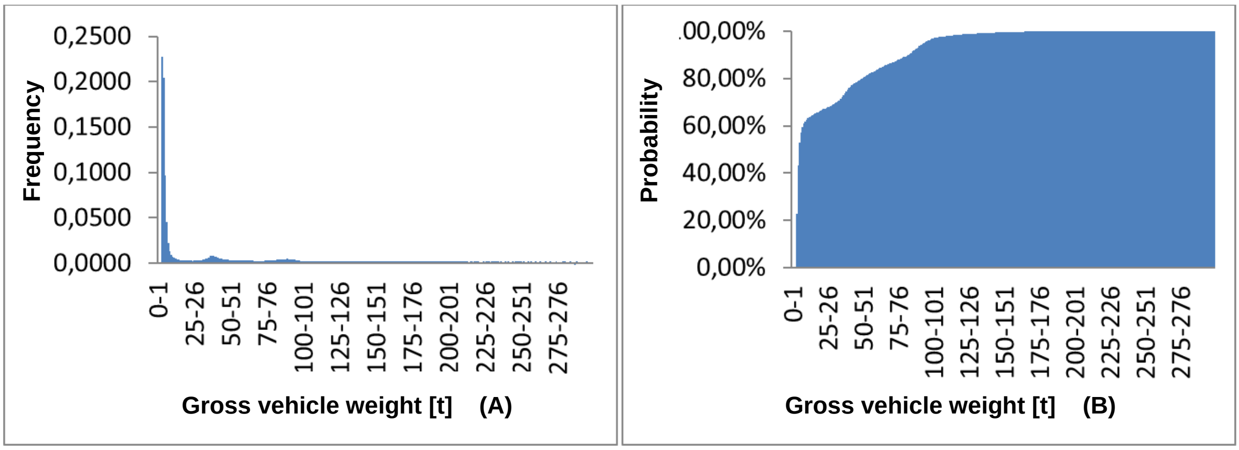

Fig. 2. Gross vehicle weight frequency (A) and the cumulative nonexiding probability (B) distribution

Vehicle distribution by number of axles showed that most, around 67% on the Latvian roads are two-axle vehicles that represent passenger cars and light commercial vehicles, the second largest group with 21% is five axle vehicle trucks - lorrys, and the third group is four-axle vehicles that constitute approximately 5% of the total traffic (**Fig. 3.**).

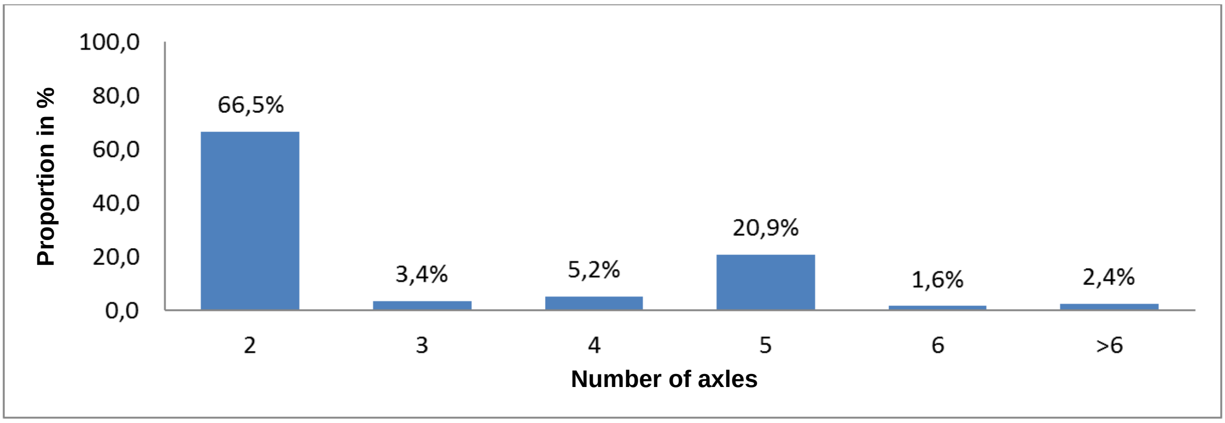

Fig. 3. Proportion of vehicles divided by number of axles

At the same time, in the analysis of two axle vehicles, it was found that in approximately 70% of cases the heaviest are the first axle. Usually though, it is assumed that the rear axle is the heaviest, but that is only in the case when the vehicle is loaded to the permissible level. This outcome is explained by the fact that heavy vehicles are often partially empty. A large part of a two-axle vehicles around 3.5 t are cargo vans, which carry a variety of items, but the weight of the goods is usually not sufficient to make the second axle the most heavy one. A similar situation exists in three-axle vehicles, where the heaviest axle turns out to be the first and second axle. For four, five and six-axle vehicles statistically the heaviest is the second axle.

Thus it can be concluded that the statistically heaviest is not always the last axle, as assumed in many load models assessed before 1984. This means that checking the load carrying capacity of the bridge must take into account the uneven distribution of axle load.

In researching actual vehicle geometry (length and axis placement), data were derived on the statistically most frequent vehicle length and axle placement. The results pointed to a large variety that must be taken into account when defining the load models.

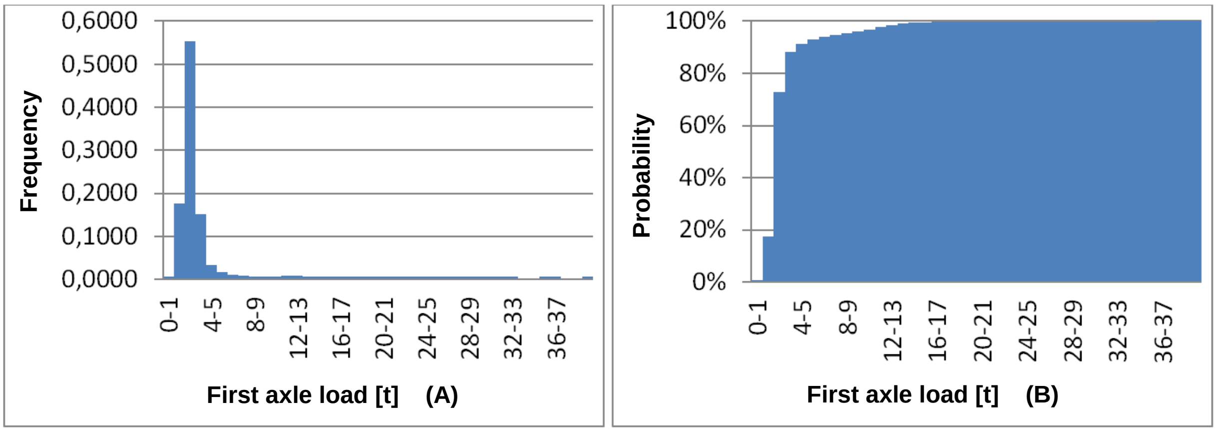

Fig. 4. Two-axle vehicles first axle load frequency (A) and the cumulative nonexiding probability (B) distribution

By studying the mass and axle weight distributions, it was found that the two-axle vehicle first and second axle weight distributions are similar shape of lognormal distribution an example is given in **Fig. 4.** In three, four, five and six-axle vehicles the mass frequency distribution is dominated by a bimodal shape, an example is given in (**Fig. 5.**) (Paeglitis & Paeglitis, Weight-in-Motion Data Analysis of Vehicle Loads of A6 Motorway in Latvia, 2012).

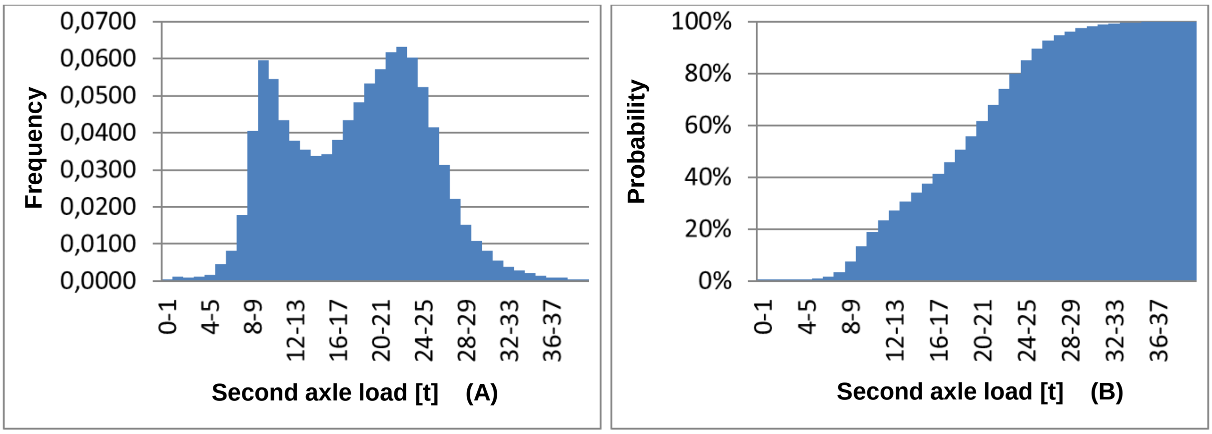

Fig. 5. The five-axle vehicles of the second axle load frequency (A) and the cumulative nonexiding probability (B) distribution

This type of the weight distribution shape indicates two possible cases – first, the movement of loaded and empty vehicles and second, that there are two separate distinctive types of vehicles. Checking the geometric parameters, two distinctive types of vehicles have not previously been identified. Thus, bimodal distributions with the first peak less disperse than the second clearly indicates the first case (above). It should be noted that the weights depend on many factors, such as a fullness of petrol tank, number of passengers, etc .

4 TRAFFIC LOAD MODELS FOR BRIDGES IN LATVIA

Traffic load is a variable which cannot be directly modelled, but the use of statistical methods makes it possible to gain reliable data on traffic load values. Based on (LVS_EN_1991-2, 2003) the load model LM1 calibration can be done using traffic loads of the repetition period of 1000 years, or a 5% of exceedance probability in 50 years. This means the non-exceeding probability of 95%.

In this study in order to find the critical traffic load models two approaches were proposed.

4.1 The first approach

The first approach is directly related to the fifth chapter of thesis where geometric and load parameters were defined. The resulting load models consist of the axle displacements with 5% of non-exceedance probability and axle load with 95% of non-exceedance probability. The 5% non-exceedance probability is needed to describe the minimum possible distance between the axles. From the resulting parameters load, models S1 - S5 have been developed. The resulting values are conservative, because it takes into account the distances between all types of vehicle axles and only the heaviest axle weight with non-exceedance probability of 95% (which is unlikely) are fitted in model. It is almost impossible to identify, but only the heaviest axle load within the range falls below 95% probability. However it covers great uncertainty and guarantees the safety and validity.

4.2 The second approach

The second approach involves real-world vehicle geometry analysis. Specific types of vehicle geometry were obtained by further analysis of the traffic composition, based on the axle displacement distribution histograms. Since some axle displacement frequency histograms were with two or three peaks, there was an additional assessment done to the data and they were broken down so that each peak represents single truck geometry. The results created loads models P-1 to P-20

4.3 Characteristic span structure types in Latvia

To determine the range of the bridges which will be affected by the new traffic load models the investigation of Latvia characteristic span structure types were done. Using VAS "Latvijas Valsts Ceļi (Latvian State Roads)" bridge management system and taking into account the typical bridge span lengths, for the calculations of simply supported beam system bridges span lengths are taken as follows: 6, 9, 12, 15, 18, 21, 24 and 33 meters, while the three-span continuously supported beam system bridges span lengths are 9 +12 +9, 12 +15 +12, 15 +18 +15, and 18 +24+18.

4.4 Evaluation of traffic load models

To determine which of the new traffic load models: S-1 to S-5 and P-1 to P-20 will inflict the largest effect, the simply supported beams bridge with the span lengths of 33, 24 and 21 m were tested using computer program Dlubal RFEM 4.05 which is based on the finite element method. A design model of bridge was made with the 9 m wide deck and two 1.5 m wide pavement on each side. The thickness of span construction was 2 m to minimize the impact on the deflections. The dead load was not included in this assessment. To replicate pedestrian load together with load models: S-1 to S-5 and P-1 and P20 the 3 kN/m2 of distributed load were placed on the sidewalks. Traffic load models are placed on the left side of the deck. The first wheel of the axle is 0.5 m from the edge of the deck and the distance between the wheels on one axle is 2 m. In order to establish the less favourable load distribution, the impact-line diagram is used.

Placing a load models on the bridge structure the maximum bending moment M1 and shear force Q2 values are obtained. All-span structure is also loaded with (LVS_EN_1991-2, 2003) load model LM1 where regulatory factor $\alpha = 1$.

Based on the results the worst possible effect on the bridge span was achieved from traffic load models S-5, P-18 and P-19 (**Fig. 6.**). Consequently, these traffic models are recommended for use when inspecting the bridge bearing capacity in Latvia.

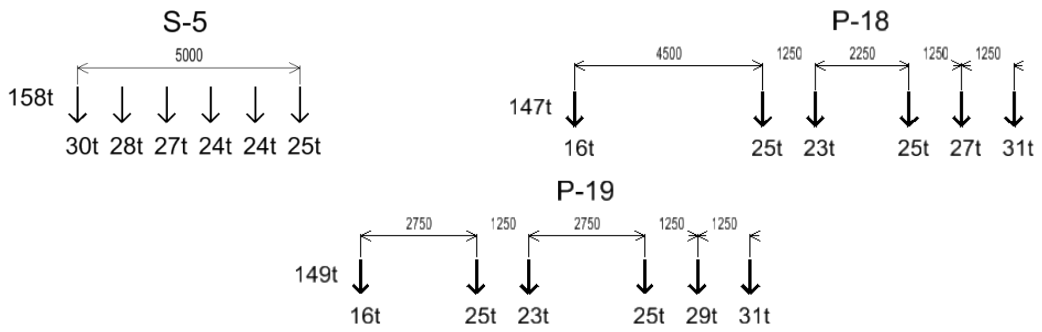

Fig. 6. Latvia typical load models S-5, P-18 and P-19

In order to simplify the application of the developed load models, they are renamed:

- S-5 to LSM1 with a total weight of 107 tons and geometry given in Fig.11.
- P-18 to LSM2 with a total weight of 147 tons and geometry given in Fig.11.
- P-19 to LSM3 with a total weight of 148 and geometry given in Fig.11.

Obtained load models significantly exceed the permitted load limits on the roads. However, analysed traffic data showed that these traffic models are possible on Latvian roads.

5 EUROCODE LVS EN 1991-2 LOAD MODEL LM1 REGULATORY FACTOR RECOMMENDED VALUE α

Eurocode allows that each Country in its National Annex document can regulate the traffic load values, according to the country-specific traffic loads through regulatory factor α.

Load regulatory factor may be determined by the bending moment and the shear force using LM1 load model (with α = 1), with are compared with Latvia typical traffic load models LSM1, LSM2 and LSM3 obtained in Chapter 6.

The results show that regulatory factor α value of continuously supported beam structures is less sensitive to span lengths then simply supported beam structures and vary from 0.58 to 0.82.

Based on the results, the regulatory load factor α can be calculated in range from 0.51 to 0.87, by taking into account the type of structure and the span length. The biggest effect on the structures was from load model LSM1.

Since regulatory factor values depend on the length of the span, two intervals can be identified: from 6 m to 18 m and from 18 m to 33 m, and for each interval regulatory factor α value are determined. Recommended values are summarized in **Table 1**.

Table 1. The recommended regulatory factor α_{Qi}, α_{qi} and α_{qr} values for bridges with spans up to 30 m

Span length	α_{Qi}	α_{qi}	α_{qr}
6 – 18 m	0.8	0.8	0.8
18-30 m	0.9	0.9	0.9

Acquired regulatory factor α_{Qi}, αqi and α_{qr} values are close to those given in the National Annex 2 of 1. Eurocode, but they are about 10% smaller. Using the regularization coefficient α values can accurately assess the load carrying capacity of the bridge, and make reasoned decisions about bridge construction or renovation, thus reducing the cost of surface transportation infrastructure maintenance.

CONCLUSIONS

Eurocode LVS EN 1991-2 "Traffic load bridges" load model LM1 (with a regulatory factor α = 1) is designed for new construction and gives an unreasonably low load carrying capacity for older bridges. Therefore, using typical Latvian road traffic load characteristics, obtained by measuring weight in motion (WIM) and using the new modelling method, the numerical traffic load models LSM1, LSM2 and LSM3 are established. These allow more accurate assessment of bridge load-carrying capacity and reduction of bridge structure maintenance costs. The developed method makes it possible to calibrate the developed traffic load models and update them as new data are received and processed, as well as adjust the traffic load model according to traffic load changes.

By applying load models LSM1, LSM2, LSM3 on bridges with span lengths up to 30 m and with a width of two lanes, resulting stresses are reduced by up to 20% compared to Eurocode LVS EN 1991-2 load model LM1 (with $\alpha = 1$), because load models LSM1, LSM2 and LSM3 characterize actual Latvian traffic load obtained by the WIM system. Bridges with greater span length and width require different load models.

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