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TRAFFIC LOAD MODELS FOR LATVIAN ROAD BRIDGES WITH SPAN LENGTH UP TO 30 METERS

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Abstract. Bridges are structures that propose the service life up to hundred years. However, the actual traffic load models significantly differ from the characteristic load models used in the design. The analysis of former design codes of bridges used in the last century in Latvia showed the considerable increase in values of characteristic traffic loads. The traffic loads proposed in *Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges* considerably increase the actual traffic loads passing Latvian bridges. Therefore, the use of the actual traffic load models for assessment of the load carrying capacity of the older bridges will extend the service life and save financial funds for the maintenance of the bridges. Earlier, the obtaining of the correct traffic data was complicated. Today after implementation of the Weight-in-Motion system, it is possible to collect vehicle information without interrupting traffic flow. This includes data of the number of axles, vehicle wheelbase, speed and axle loads that describes the actual loading cases on the roads and bridges. The analysis of the recorded data of Weight-in-Motion the system enabled to obtain the load distribution diagrams, to determine the position of the heaviest axel, traffic speed and intensity values. The obtained results of statistical analysis of actual traffic loads allowed developing the integrated traffic load models for bridges, based on actual traffic load in Latvia. Obtained integrated traffic load models for bridges in Latvia is used for evaluation of the value of the adjustment factor α of the load model LM1 proposed in *Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges.*

Keywords: bridge, integrated traffic load model, statistics, vehicle load, Weigh-in-Motion (WIM) system.

1. Introduction

One of the research priorities of the European Union (EU) is the investigation of the methods for the improvement of road network infrastructure. Compared to the previous years, the construction of the new roads and bridges is met less often; hence, greater investment in maintaining the functioning of existing infrastructure is needed. Moreover, to ensure appropriate safety standard implementation. Over the past years, the number of vehicles on EU roads has increased considerably. The growth of traffic flow initiates the changes in the composition of the types and weight of vehicles.

Today, on the Latvian road network 936 bridges are maintained. From reinforced concrete there are 880 bridges, from stone and bricks there are 16 bridges; there are 33 steel bridges and seven timber bridges. Most of them were built after the World War II. Regular bridge inspections have shown that about 60% of the existing bridges have damages that to a various extent affect their load carrying capacity. Considering the current financial situation and the limited financial funds dedicated to the necessary bridge reconstruction or repair, it is important to clarify the actual traffic load effect on the bridge structure, to evaluate structural capacity and to determine the limits within which the existing bridge structures are safe to be operated.

Previously, the collection of data of the traffic loads was a long and time-consuming process that required the traffic interruption during the measurement process. Vehicles were counted and weighed in specified locations. The obtained data was used for traffic load forecasting. The recorded data was not always sufficient and accurate. However, the characteristic load models for the bridge code were developed based on this data. In the recent decades, the new methods for obtaining the exact data of the traffic loads have been developed. One of the methods is the Weight-in-Motion (WIM) (Miao, Chan 2002; Nowak, Rakoczy 2013) or weighting vehicles in motion, which is used in this study. This method uses a measurement system, which allows the measure of gross weight, axle load, axle number and speed of each vehicle in motion.

For structural analysis of bridges, the traffic load models have been used since 1900. Since the beginning of

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the past century, the load models have changed more than six times. Each time the value of the gross weight of the vehicles has increased, thus the new bridge was designed using new higher values of load models (Paeglitis, Paeglitis 2010). With increasing knowledge about the structural behaviour of bridge structures, the methods of structural analysis become more and more precise.

Today, it is possible to go one-step further and for the evaluation of load carrying capacity of existing bridges to use the actual load models that comply with actual traffic composition on Latvian highways. The paper deals with analysis of actual traffic load composition and vehicle characteristics on Latvian highways. The main objective of this study is to develop a statistical integrated model for the traffic loads on highway bridges based on the new Weigh-in-Motion (WIM) data. The obtained results allowed evaluate the value of the adjustment factor α of the load model LM1 proposed in *Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges.*

2. 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 intended primarily for the design of new structures. The use of Weigh-In-Motion data for the analysis of bridge live load has been investigated by many researchers (Laman, Nowak 1997; Li *et al.* 2013; Nowak, Heywood 1989; Nowak, Hong 1991; Nowak 1993; Nowak, Rakoczy 2013; Steenbergen, Vrouwenvelder 2010; Van De Lindt *et al.* 2005). Several of traffic load models are developed by using a short time observation of heavy traffic flow and by using the extrapolation of the long-term load effects. All moving vehicles generate additional dynamic effects on bridges (Keenahan *et al.* 2014; O'Brien *et al.* 2013; Paeglitis, Paeglitis 2013). Traffic load-induced effects depend on many variables such as the vehicle weight, axle weight, axle spacing, speed, etc. The carrying capacity assessment methods used for in-service bridges are based on the technical assessment and real-time traffic analysis of the structures. Various studies show that the actual traffic load is up to 50% less than that in the standards (O'Brien *et al.* 2012). The traffic loads, given in *Eurocode 1, Part 2,* ensure the design of bridges with large carrying capacity margins, which are sometimes not economically viable. By studying the adjustment factor α value, that according to Latvian national annex is invariable for tandem system and uniformly distributed load, it is found that it is considerably dependent on both the bridge span length and width of the roadway and on the road category.

Since the composition of traffic flow differs from country to country, therefore direct use in any country without taking into account the specific traffic conditions is not purposeful. This requires determination of the appropriate load models namely for Latvia using long-term WIM data (Paeglitis, Paeglitis 2013).

Further, the analysis of historical and currently used traffic load models for bridges in Latvia and their load value increases was performed. It was found that vehicles used today, compared to those historically used, are longer, with a higher number of axles and a larger distance between them, thus, their effect on the load bearing construction of the bridge in many cases will be shorter, and only some axles simultaneously fit on a small or mid-span bridge. Therefore, it is important to clarify the typical traffic load patterns of Latvian road bridges and integrate them into the small and medium-span bridges carrying capacity assessment of existing bridges.

3. Data analysis

Part of the WIM data was excluded from further processing due to a low validity. It was carried out by applying data filters and using 4 criteria:

– the 1st criterion is the max permissible axle load, which is adopted equal to 40 t,

– the 2nd criterion is the total weight max of the vehicle, which is assumed equal to 300 t,

– the 3rd criterion requires a min total vehicle weight of 3.5 t (only heavy vehicles are taken into account),

– the 4th criterion is the speed of the vehicle (limit is set at 150 km/h, more than the permitted speed limit, however, due to a reckless driving of vehicle drivers much of the heavy vehicle data would not be included).

The next step in data processing is the establishment of the template file for each set of parameters. The 1st template file includes information on the axle 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 2nd template file was created to evaluate the determinative vehicle axis and the total number of vehicles divided by the number of axles. The 3rd, 4th, 5th, 6th and 7th template file is created similar to that described above the only difference is in the number of axles, which are accepted as 2, 3, 4, 5 or 6, accordingly. When processing the data, 46 files were created that contained information about 1 million vehicles. In each data file the complete traffic information of 33 weeks was used. The methods of the traffic load analysis are given in Fig. 1.

For the selection and representation of geometrical parameters, the frequency and cumulative distribution histograms are widely used (Bailey 1996). For the design of histograms the algorithm showed in Fig. 1 was used. The variable number n was determined for every measured value that reached 1 million, and range r depends on the maximum and minimum values of measurements. Both the number and size of variable classes in this research were determined according to the necessary accuracy. The total axle loads and maximum axle load distribution load class size was adopted as 0.2 t, and distributed load – 0.2 t/m, while vehicle gross weight distribution class size was equal to 1 t. For individual 2, 3, 4, 5 or 6 axle vehicles

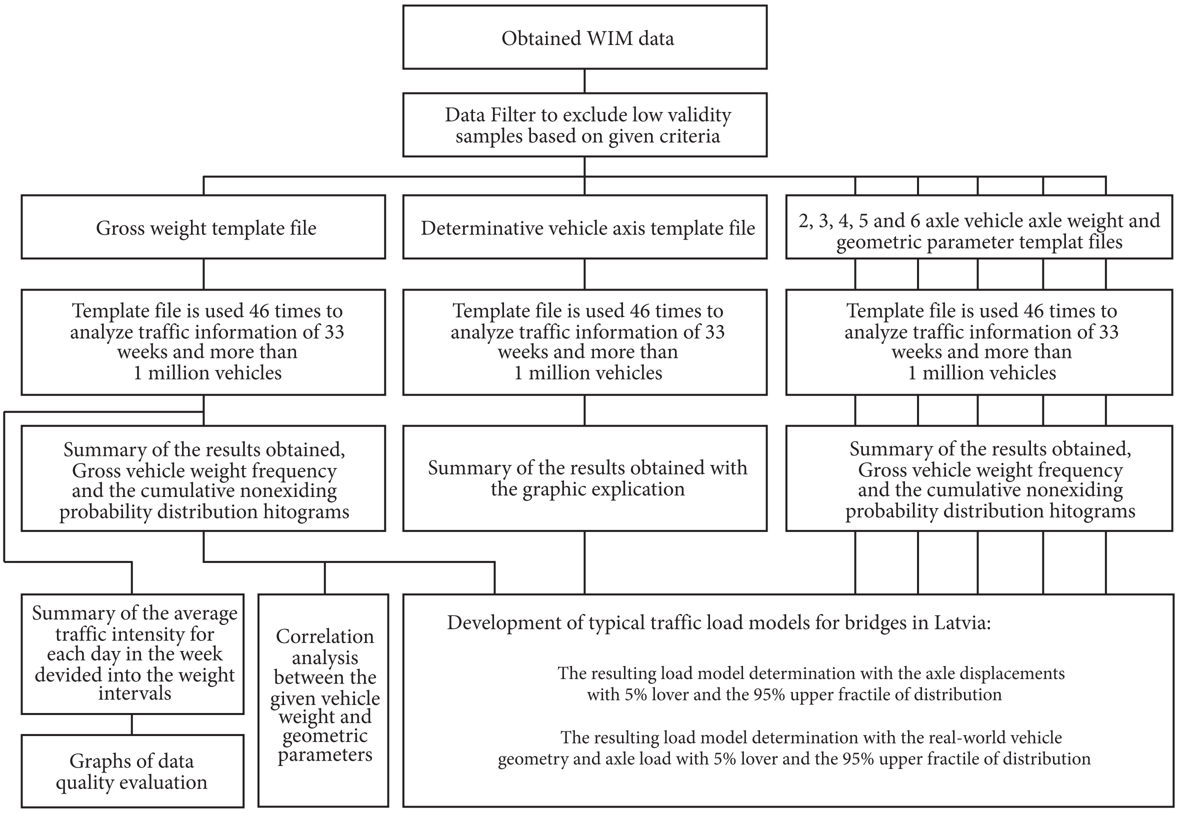

Fig. 1. Flowchart of the traffic load analysis method

the weight and axle placement parameters were defined following the class sizes: speed distribution – 5 km/h, vehicle length – 0.5 m, distribution of the axle load – 1 t, and distribution of the axle separation – 0.5 m.

The absolute class frequencies n_j is calculated next by counting how many random elements are in each class interval. To select and count the number of elements within each class of variables the *MS Excel* function COUNTIF is used. The relative class frequency f_j is determined by dividing the absolute frequency of class N_j with the total number of elements in the sample *n*.

$$\sum_{1}^{n_c} f_i = 1. \tag{1}$$

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 $N_i = j$, inclusively. 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 $F_j = 1$.

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

The resulting values were summarized in the table and used as a base for 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 is used. This means that the larger amount of collected data the better and more accurate the values of probability are described. Since in this study a large amount of data is used, it is assumed that the relative cumulative frequency diagram values represent the necessary probability.

WIM data used for this study was obtained by the measuring equipment which was installed on the motorway A4 (Baltezers–Saulkalne) between roads P5 and A6 (Riga–Daugavpils–Kraslava–Belarussian border (Pāternieki) from 2002 until 2008. The measuring equipment was located 500 m before intersections in this roadway, thus, providing free traffic conditions and good data collection situation.

The WIM system has recorded data of more than 17 568 000 vehicles, about 244 000 vehicles in a month during six years. Initial processing of the data showed that the WIM sensor errors in the 1st year was about 5% in the 2nd year – 15% and in 3rd year over 25% (Vaziri *et al.* 2013). Therefore, not all the recorded data was useful for further analysis. This study uses the data recorded in 2004. Totally, the data of 1 172 842 vehicles was recorded in 2004. The statistical analysis showed that the weight of 449 218 vehicles was less than 3.5 t, but the weight of 663 101 vehicles exceeded 3.5 t. The data of 60 523 vehicles was incomplete and excluded from the further analysis. The statistical analysis of recorded data showed that 861 165 vehicles or 79.82% are 2-axle vehicles. The 2nd largest group was the 5-axle vehicles – 12.48%, followed by 3-axle, 4-axle and 6-axle vehicles with 6.25% of the total number of considered vehicles.

4. Characteristic traffic loads

Analysis of gross vehicle weight showed that the largest group of vehicles on roads are cars with a mass around 3.5 t, the 2nd largest group of vehicle weigh is around 37 t and the 3rd group with a mass of 90 t (Fig. 2). The max vehicle weight of 94–95 t is determined with 95% probability and the remaining 5% of vehicles with a mass of up to 300 t what occurs very rarely only with the special permits of the authorities.

Distribution of vehicles by the number of axles showed that around 67% of vehicles are 2-axle vehicles representing passenger cars and light commercial vehicles, the 2nd largest group with 21% is 5-axle trucks – lorries, and the 3rd group is comprised by 4-axle vehicles that makes approximately 5% of the total traffic volume (Fig. 3).

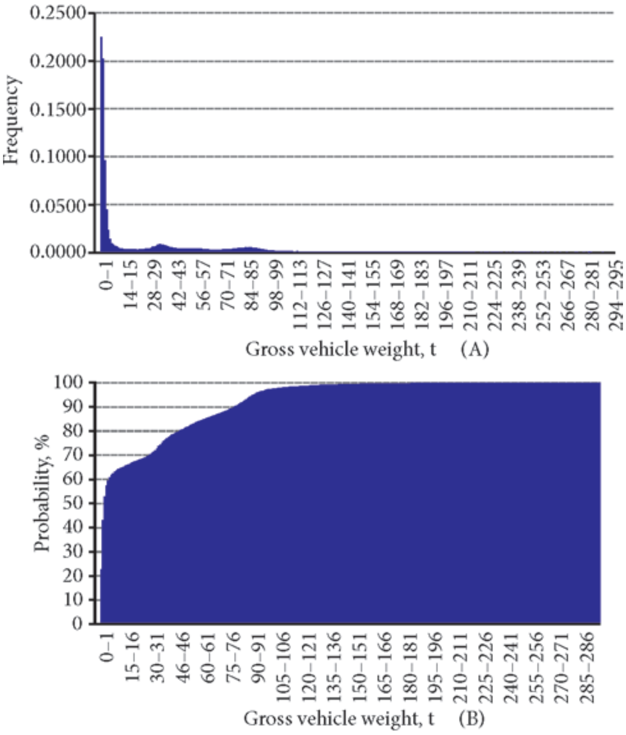

Fig. 2. Vehicle gross weight frequency distribution (A) and the accumulative probability distribution (B)

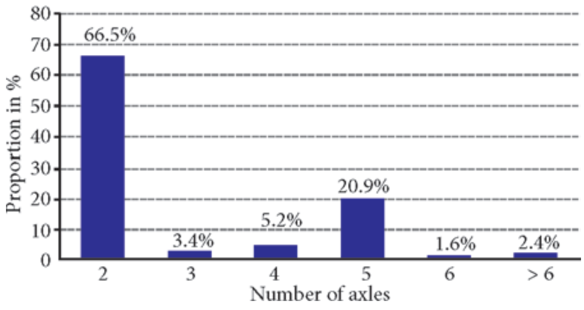

Fig. 3. Proportion of vehicles depending of the number of axles

At the same time, the analysis of 2-axle vehicles showed that the 1st axle is the heaviest approximately in 70% of cases. Usually, it is assumed that the back axle of the vehicle is the heaviest one but this is only in case if the vehicle is loaded to the permissible level. This outcome shows the fact that the heavy vehicles are often partially empty. A large part of 2-axle vehicles around 3.5 t are light trucks, which carry a variety of items, though the weight of goods is usually not sufficient to make the 2nd axle the heaviest one. The similar situation is observed for 3-axle vehicles, where the heaviest axle is also the 1st and 2nd axle. For 4-axle, 5-axle and 6-axle vehicles, statistically the heaviest is the 2nd axle. This allows concluding that the statistically heaviest is not always the last axle, as this is assumed in many load models used before 1984. The obtained results showed that the uneven distribution of axle load in multi axle vehicles influences the assessment of the actual load carrying capacity of the bridges.

When studying actual vehicle geometry (vehicle length and axis location), the recorded data were derived on the statistically most frequently existing vehicle length and axle locations. The results showed a large variety of data that are taken into account in the load models.

When studying distribution of mass and axle weight, it was found that in the 2-axle vehicle the 1st and the 2nd axle weight distributions are similar to the shape of lognormal distributions (Fig. 4). A bimodal shape dominates in

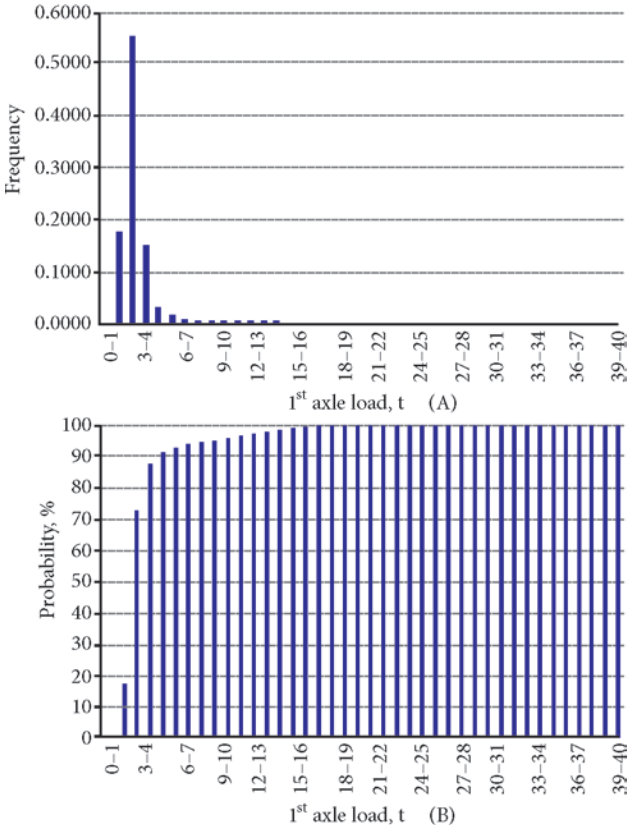

Fig. 4. The 1st axle load frequency (A) of 2-axle vehicles and the accumulative probability distribution (B)

the mass distribution frequency in 3-axle, 4-axle, 5-axle and 6-axle vehicles, as showed in the example in (Fig. 5).

Bimodal shape of the weight distribution indicates two possible causes: the movement of loaded and empty vehicles or the movement of two distinctive types of vehicles. By checking the geometric parameters, two distinctive types of vehicles have not identified previously. Thus, the 1st peak dispersion in the bimodal distributions is lesser than the dispersion of the 2nd peak because the empty vehicle mass has lesser dispersion. The vehicle mass depend of many factors, such as fullness of petrol tank, number of passengers, etc.

5. Integrated traffic load models for bridges in Latvia

Actual traffic load is a variable that in the direct way is difficult to be modelled but the use of statistical methods makes it possible to obtain characteristic values of actual traffic load. For calibration of the load model LM1 proposed in *Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges* the actual traffic load values are used with the return period of 1000 years, or 5% lower and 95% upper fractile value of the Gaussian statistical distribution diagram. Two approaches were used for obtaining the characteristic traffic load models.

The first approach use geometrical and load parameters obtained previously. Integrated traffic load models describe the disadvantageous loading situation, taking into account the distance between the axes with the 5% lower and the 95% upper fractile of distribution. The 5% fractile of distribution describes the minimum possible distance between the axles. From the resulting parameters eight integrated traffic load models are developed. The resulting values are conservative, because they take into account the distances between all types of vehicle axles and only the heaviest axle weight with 95% fractile of distribution fitted in the model. However, the approach covers great uncertainty and guarantees the safety and validity.

The second approach involves the determination of existing vehicle geometry analysis for establishing the traffic load models. The specific types of the vehicle geometry were obtained by further analysis of the traffic composition based on the axle distance distribution histograms. Because some histograms of the axle distance frequency were with two or three peaks, an additional assessment of the data intervals was performed. The intervals were divided in a way that each peak represented single truck geometry. In the result twenty integrated traffic load models were developed.

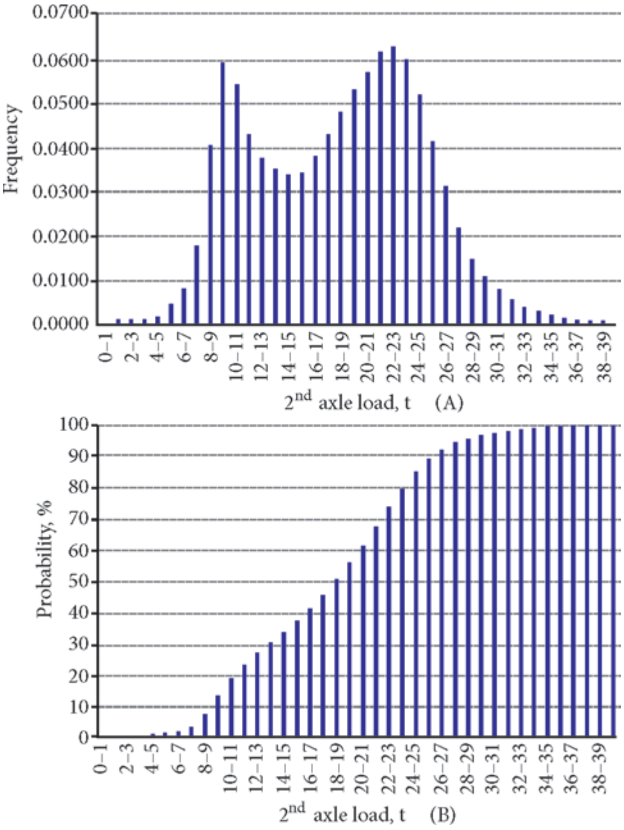

Fig. 5. The 5-axle vehicles of the 2nd axle load frequency (A) and the accumulative probability distribution (B)

For clarifying the impact of the developed integrated traffic load models on bridge span structures, the most common bridge systems and types used on Latvian roads were selected. For this purpose the Bridge Management System (BMS) of the Latvian Road Administration was used. According to BMS data, 73% of all bridges in the bridge stock are simply supported beam or slab systems followed by 11% continuous beam or slab systems and 14% of other span systems. Since the simply supported systems compose the larger part of bridges in Latvia for the evaluation the bridges with span lengths: 6 m, 9 m, 12 m, 15 m, 18 m, 21 m, 24 m and 33 m were chosen. For continuous system three span bridges with span lengths: 9 m + 12 m + 9m; 12 m + 15 m + 12 m; 15 m + 18 m + 15 m and 18 m + 24 m + 18 m were chosen.

To determine the major effects of the developed integrated traffic load models on simply supported and continuous beam bridge systems with the span length mentioned before, the software *Dlubal RFEM 4.05* which is based on the finite element method was used. The modelled cross-section of bridge consisted of 9 m wide deck and two 1.5 m wide sidewalks on each side. In this assessment, the dead load was not included. The 1st wheel of the axle is 0.5 m from the deck edge and the distance between the wheels of one axle is 2 m. In order to establish the less favourable load distribution, the impact-line diagrams are used.

By placing the integral traffic load models on the bridge structure the maximum bending moment and shear force values are obtained. All-span structure is also loaded with the load model LM1 proposed in *Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges* with the adjustment factor α = 1. The obtained results showed that the maximum efforts in bridge structures induced the integrated traffic load models LSM1, LSM2 and LSM3 presented in Fig. 6. Consequently, these models are applicable as characteristic traffic load models for the assessment of the bridge load bearing capacity.

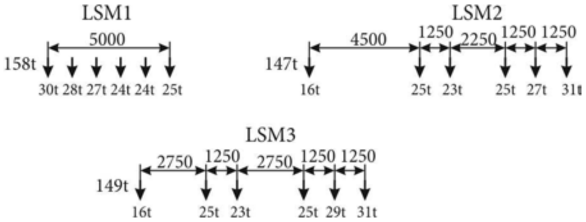

Fig. 6. Most important integrated traffic load models based on actual traffic loads in Latvia

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

6. Recommendation for the value of adjustment factor α in Latvia

Eurocode 1 allows that the National Annex document regulates the traffic load values, according to the actual traffic loads in each country through the adjustment factor α. The National Annex document in Latvia provides that the adjustment factor α is identical for uniformly distributed load (UDS) and double-axle concentrated loads (tandem). Such approach allowed comparing the load carrying capacity of bridges, by expression of the permitted characteristic loads in load model LM1 proposed in *Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges* with the value of adjustment factor α. This approach was used to compare the influence of integrated traffic load models LSM1, LSM2 and LSM3 on the efforts in bridge structures with the impact from the load model SM1 of *Eurocode 1*.

The efforts (bending moments, shear forces) from the loading with the integrated traffic load models LSM1, LSM2 and LSM3 on the bridge structures were compared with the efforts caused from the load model SM1 of the *Eurocode 1* with the adjustment factor α = 1. This correlation express the value of adjustment factor α. From the integrated traffic load models LSM1, LSM2 and LSM3 the adjustment factor α for continuously supported beam structures vary from 0.58 to 0.82, and for simply supported beams ranges from 0.51 to 0.87, with the highest impact from integrated load model LSM1.

Since the efforts depend on the length of span, two intervals are identified: from 6 m to 18 m and from 18 m to 33 m, and for each interval the adjustment factor α value is determined. The recommended values are summarized in Table 1.

The obtained results showed that actual traffic loads on Latvian roads cause 10% less efforts than proposed in *Eurocodes 1* load model LM1. Using the obtained values of adjustment factor α it is possible to make the reasoned decisions on bridge construction or renovation, thus, reducing the cost of bridge maintenance and conservation.

Table 1. The recommended values of adjustment factor α for bridges with spans up to 30 m

Span length, m	α
6–18	0.8
18–30	0.9

7. Conclusions

Safety and reliability of bridge infrastructure are a major target for bridge authorities in Latvia. A substantial part of existing road bridges had damages and needs intervention or conservation measures. Reduction in the cost of repair or potential intervention of the bridge is a very important aspect for bridge authorities. The obtained integrated traffic load models LSM1, LSM2 and LSM3 correctly reproduce the load effects induced by actual traffic data obtained by using Weigh-In-Motion measurements on Riga by-pass. The method developed enables to calibrate the obtained integrated traffic load models and update them with new data, as well as to modify the traffic load model with the new load effects considered.

The load effects of integrated traffic load models LSM1, LSM2 and LSM3 are compared with the effects of the load model LM1 proposed in *Eurocode 1: Actions on Structures – Part 2: Traffic Loads on Bridges* (with the adjustment factor α = 1) on bridges with the span length up to 30 m and the carriageway width of two traffic lanes. According to the obtained results, resulting stresses from the integrated traffic load models LSM1, LSM2 and LSM3 decreased by up to 20% compared to the stress from the *Eurocodes 1* load model LM1 with the adjustment factor α = 1. The use of integrated traffic load models for the assessment of load carrying capacity of existing bridges in Latvia will reconsider the scope of intervention to save costs for reconstruction and replacement of the span structures.

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