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Intensity of load on road bridges in a congestion situation

Abstract: The work analyzed the safety of road bridges during their exploitation in the situation of maximum load. Such bridge loads occur during acceptance tests of the object when the system of cars on the roadway is programmed. Considered in the work is the situation of full load on bridges occurring during a road congestion. Then the layout of the vehicles is inherently random and several of them can form a system of maximum, local load. The results of measurements during the actual congestion created on the bridge with a suspended diagram were related to the results of numerical analyzes. A two-beam span model and a dual carriageway load system in the congestion were adopted. As an extreme case, the load from two vehicles was considered at work, but in a small bridge. A replacement load algorithm was used for comparative analysis.

Keywords: Safety of road bridge, Congestion, Numerical analysis

Maximum mobile loads of road bridges

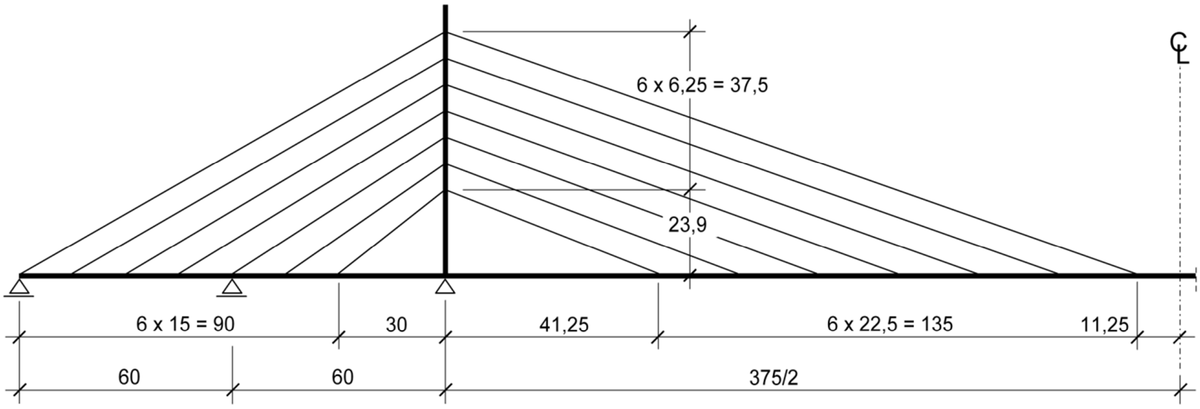
After the construction of bridges of great transport importance, acceptance tests are carried out [1, 2, 3]. In the case of a small span, motor vehicles are placed on the entire surface of the roadway, in accordance with the shape of the influence surface of the analyzed static quantity [4]. The load is limited to the bridge section with the largest ordinates of the influence surface when testing a large-span bridge. This reduces the already large number of cars used in the study [5]. Transports of large elements [6] as non-normative journeys are a separate issue [1, 3].

In the event of congestion on the bridge's exit road, the entire bridge may be fully loaded [7]. The arrangement of vehicles is then inherently random, so there are both trucks with axle configurations and loads as well as passenger cars. The common features of both types of loads (test and congestion) are the static impact of vehicles on the span structure and the minimum distances between the bumpers of the vehicles (they are smaller in the test load situation). The difference between these loads is that in the event of congestion, the layout of the vehicles is arbitrary - it is not related to the static scheme so that some vehicles may unload the structure.

In the case of bridges with small spans, the random arrangement of vehicles on the bridge, as in a jam, does not pose a threat. Because during the acceptance test of such a bridge, the maximum span area is filled with the heaviest cars in a system consistent with the impact area of the analyzed static quantity [1, 4]. When the communication system is a dual carriageway and the spans are comparable to the length of the truck, the situation of two vehicles meeting on the bridge is of great importance [1]. It may be cars passing each other on the facility when the traffic is going in two directions, or there may be parallel driving on a motorway-type facility. This situation is more common on a small bridge than during congestion.

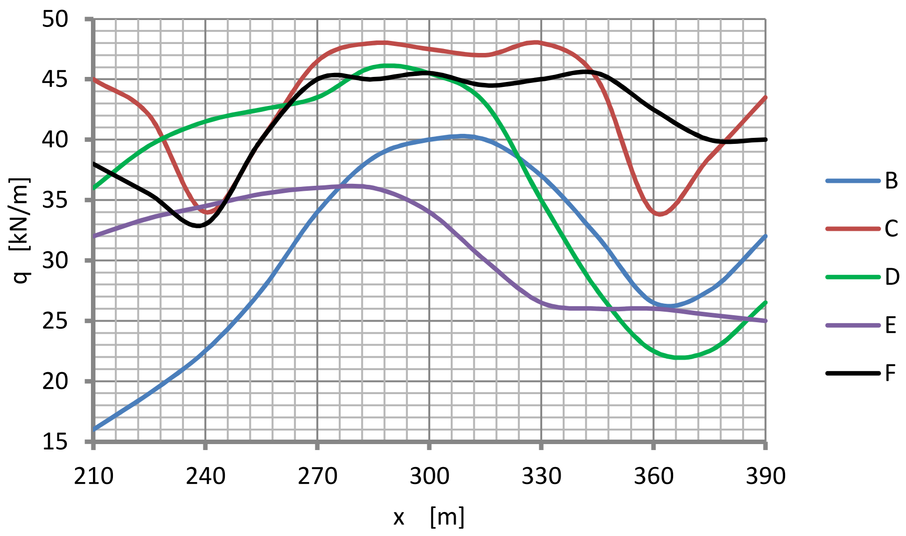
Congestion at the exit from the bridge in Płock

The situation of the congestion formation on the bridge can be used to determine the load intensity along the bridge carriageway. The use of facility monitoring was used to analyze such a load arrangement in the bridge with a suspended diagram in Plock, as shown in Fig. **1**. Based on the algorithm based on the function of the influence of axial forces in the shrouds, presented in [7, 8], changes in the forces in the shrouds were considered with a very slow but variable arrangement of vehicles on the bridge. The calculations took into account the load on the entire bridge and the shape (and sign) of the lines of influence of axial forces in the shrouds. Thus, the effects of increasing and decreasing the internal forces were taken into account. Due to the limited measurement base (small number of shrouds with measuring devices), an iterative approach was used to analyze the central part of the suspended span over the section $210 < x < 390$ m in the final phase.



1. Static diagram of half of the structure

The load in the congestion concerned two occupied lanes from one direction of travel when two adjacent lanes from the other direction were free. The processed measurement results obtained in this way are given in Figure **2** as the intensity of the load per roadway. Thus, this is the average value obtained from the lanes. Due to the random arrangement of cars on the graphs, there is a complex shape of the function q(x). Extreme q was created where trucks with full loads collided. Situations were selected for analysis in which the shrouds showed the greatest increases in strength (diagrams C–F). Schemes A and B were used to test the numerical algorithm [7].



2. Intensity of the span load in the event of congestion on the bridge in Plock

From the results given in Figure **2**, the load on the road lane can be calculated as a surface force. If the width of the carriageway is assumed to be b_j = 3,5 m, the maximum value of q gives the load

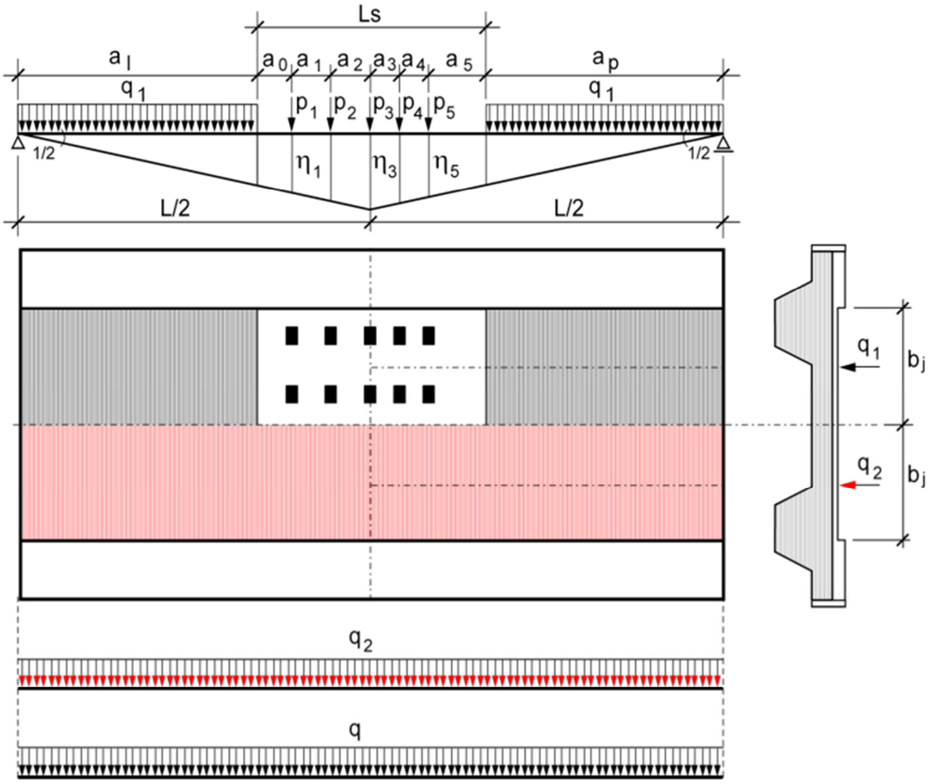
$$p = \frac{q}{b_j} = \frac{48}{3{,}5} = 13{,}7 \ kN/m^2 \tag{1}$$

The value given above is very high compared to loads of old bridges, e.g., Grunwaldzki in Wrocław, because p_{DIN} = 5,0 kN/m^2 [1]. Also, the load distribution according to PN [9] for class A was p_{PN} = 4,0 kN/m^2. The value given in (1) is comparable to that recommended in EN [10]. It is important that in the above-mentioned cases of standard recommendations, additional vehicles were used: a steam roller in DIN, a K800 vehicle in PN, or a system of concentrated forces in EN. The design load systems were and are composed of forces distributed over the road surface, supplemented by concentrated forces. Such a system is also considered in the paper as a congestion load model.

When comparing the load intensity p given in (1) it should be taken into account that this is a local value. Part of the function q(x) given in Fig. **2** shows large fluctuations also outside the analyzed area. In assessing the safety of the bridge, the random arrangement of cars should also be taken into account, i.e. their share in the areas that relieve the element. Because in such a bridge, the influence functions have a complex shape [1, 7, 8]. For the reasons given, a simple model of the bridge structure and a dual carriageway system were adopted in the further part of the work.

Load comparison algorithm

A comparative algorithm [1] is used to convert complex load systems into a simple, homogeneous equivalent load, e.g., a uniformly distributed force. In order to simplify the computational model, a bridge with a double-beam structure [11] and a freely supported scheme was adopted in the work, as shown in Figure **3**. Also for this purpose, a dual carriageway load system was used on the bridge, and the surface load was reduced to a linear one, evenly distributed in the middle of the roadway, as q_1 and q_2. For the comparative analysis, the bending moment in the middle of the span of girder 1 was assumed as the internal force.



3. Diagram of span loads in the event of congestion

The result of the calculations is the equivalent load q distributed evenly along the entire length of the span with different values on both roadways

$$p_1 = \frac{q}{b_j}\alpha_1 \tag{2}$$

and

$$p_2 = \frac{q}{b_j}\alpha_2 \tag{3}$$

Thus, the coefficients α_1 and α_2 are load multipliers as per EN [10] for lanes. Such distributed forces cause a bending moment in the middle of the span of girder 1

$$M = (k_{11}\cdot\alpha_1 + k_{12}\cdot\alpha_2)\frac{q\cdot L^2}{8} \tag{4}$$

In this formula, k_{11} and k_{12} are the transverse load distribution coefficients [1, 4], and their sum is assumed to be 1. The second load system, compared with it, comes from congestion, i.e. forces distributed over the span lengths q_1 and q_2. The load from the congestion is supplemented by a motor vehicle in the form of concentrated forces occurring in lane 1. This arrangement of forces causes a bending moment

$$M = q_1\cdot k_{11}\left(\frac{L^2}{8} - A\right) + q_2\cdot k_{12}\cdot\frac{L^2}{8} + k_{11}\sum_{i=1}^{n} P_i\cdot\eta_i \tag{5}$$

The formula's final term is derived from the concentrated forces P and the ordinates of the lines of influence of the bending moments η located in the middle of the girder's span. The value A is the area free of the load q_1 on lane 1, as in Figure **3**

$$A = \frac{1}{8}\left[L^2 - 2\left(a_l^2 + a_p^2\right)\right] \tag{6}$$

Assuming that the model defines the parameters of the bridge structure, i.e. L, k_{11} and k_{12}, appearing in formula (5) and the loading coefficients of the road lanes α_1 and α_2 appearing in (4) have been adopted, the equivalent load is defined as

$$q = \frac{1}{K}\left[q_1 \cdot k_{11} + q_2 \cdot k_{12} + \frac{8k_{11}}{L^2}\left(-q_1 \cdot A + \sum_{i=1}^{n} P_i \cdot \eta_i \right)\right] \quad (7)$$

where

$$K = k_{11} \cdot \alpha_1 + k_{12} \cdot \alpha_2 \;. \quad (8)$$

When considering a dual carriageway bridge with traffic in both directions, there is no special justification for assuming different loads on its carriageways 1 and 2. Thus, $\alpha_1 = \alpha_2 = 1$ and $q_1 = q_2$ and hence $K = 1$. formula (7) the equation is formed

$$q = q_1 + \frac{8k_{11}}{L^2}\left(-q_1 \cdot A + \sum_{i=1}^{n} P_i \cdot \eta_i \right) \quad (9)$$

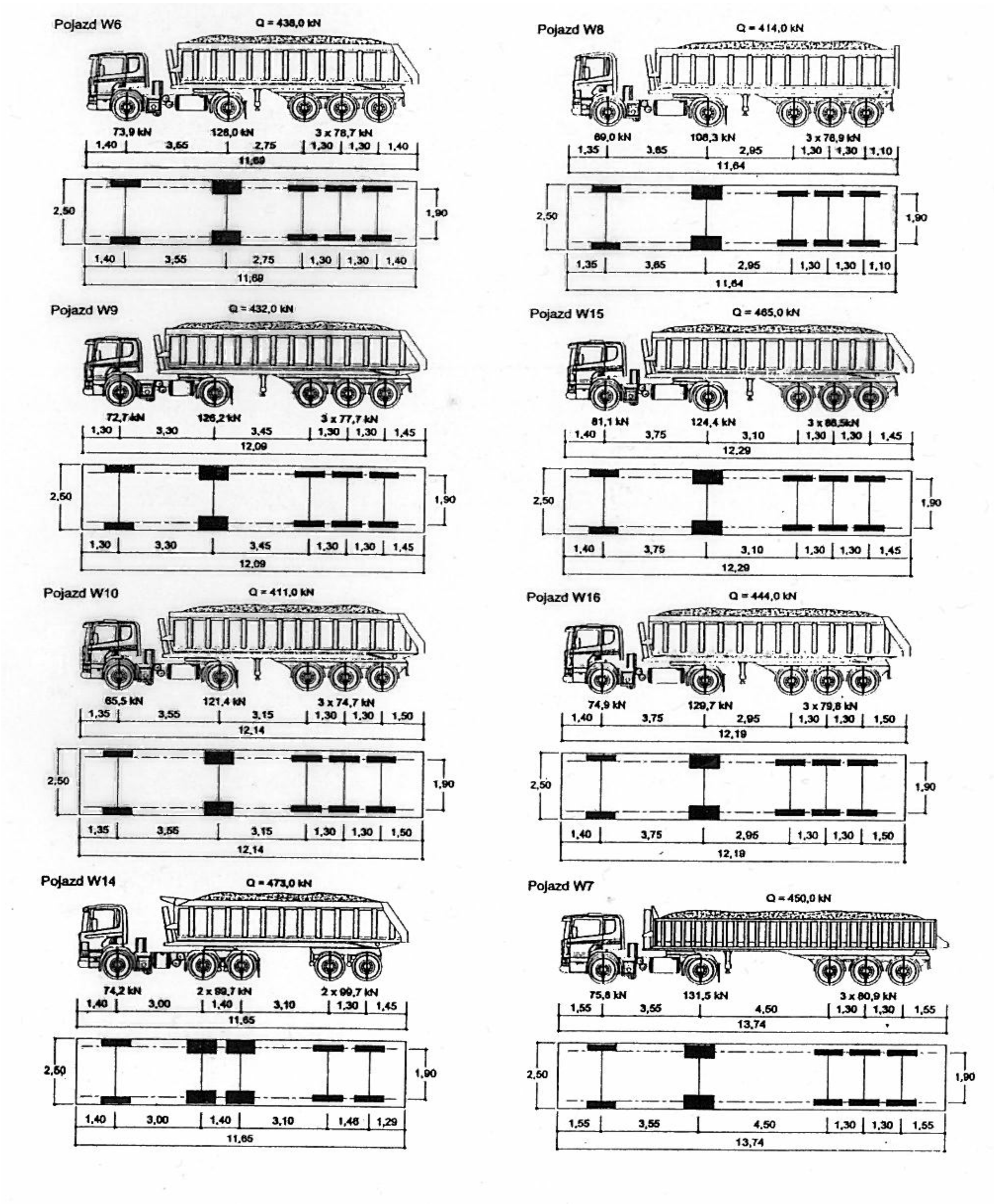
In the examples of analyzes given in the paper, it is additionally assumed that the loads in the congestion are consistent with the equivalent load, i.e., q1 = q2 = q. With this assumption, formula (9) simplifies to the form

$$q = \frac{1}{A}\sum_{i=1}^{n} P_i \cdot \eta_i \quad (10)$$

Parametric analysis of the congestion effect

In order to estimate the value of the equivalent load q, the heaviest motor vehicles used for transporting loose materials on the construction site were adopted for the analysis. These vehicles are listed in two groups, as shown in Figures 4 and 6. Technical parameters are listed in tables 1 - 4. The variable parameter of the analysis is the span length L.

Fig. **4** shows a diagram of loading with W -type vehicles with force symbols and wheelbases given in tables 1 and 2.



4. Axle arrangement in the considered W-type vehicles

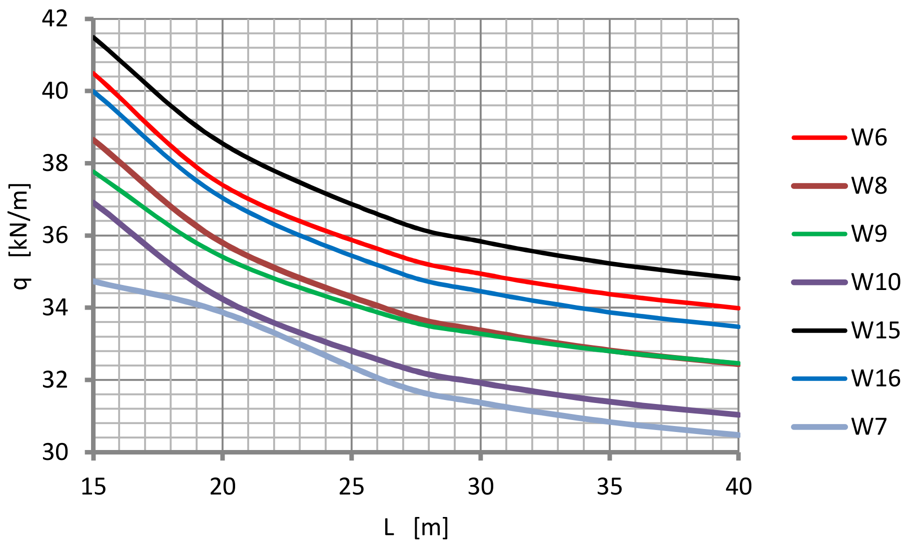
Tab. 1. Axle loads in construction vehicles [kN]

Vehicle	P_1	P_2	P_3=P_4=P_5	Q
W6	73,9	126	78,7	436
W7	75,8	131,5	80,9	450
W8	69	108,3	78,9	414
W9	72,7	126,2	77,7	432
W10	65,5	121,4	74,7	411
W14	74,2	99,7	99,7	473
W15	81,1	124,4	86,5	465
W16	74,9	129,7	79,8	444

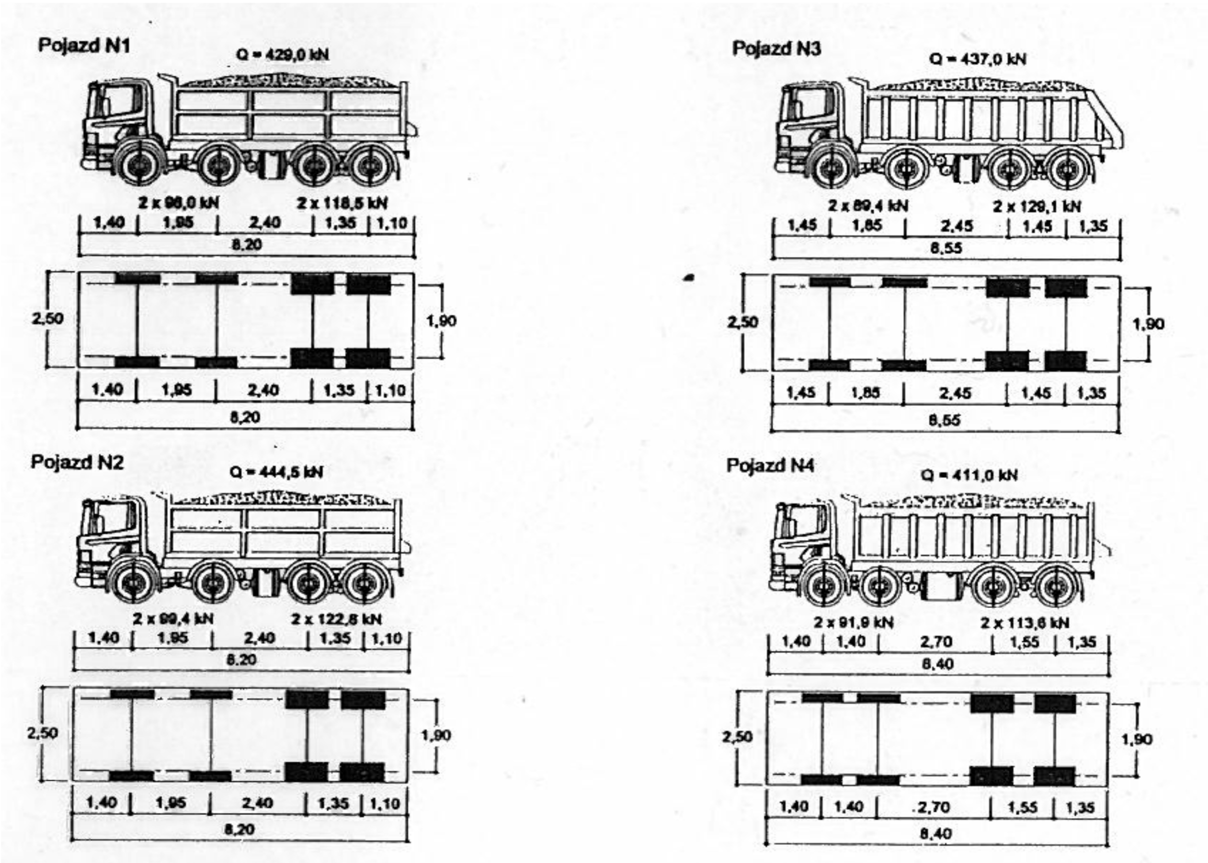
Tab. 2. Geometrical parameters of construction vehicles [m]

Vehicle	a_0	a_1	a_2	a_3 = a_4	a_5	L_s
W6	1,4	3,55	2,75	1,3	1,4	11,7
W7	1,55	3,55	4,5	1,3	1,55	13,75
W8	1,35	3,65	2,95	1,3	1,1	11,65
W9	1,3	3,3	3,45	1,3	1,45	12,1
W10	1,35	3,55	3,15	1,3	1,5	12,15
W14	1,4	3,0	1,4	3,1/1,45	1,2	11,55
W15	1,4	3,75	3,1	1,3	1,45	12,3
W16	1,4	3,75	2,95	1,3	1,5	12,2

Figure **5** shows the calculation results when the span ranges 15 < *L* < 40 m. The length of section L_s given in Figure **3** is the distance between buffers increased by 1 m on each side. Despite slight differences in vehicle geometry and axle loads, the graphs are dispersed. The highest values of q are obtained in the case of the W15 car. As expected, the largest *q* values are obtained for a short-span bridge. The maximum values of *q* from the graphs shown in Figures **2** and **5** are similar. Therefore, the intensity of loads from congestion on the bridge in Plock is comparable to the average road structure and motor vehicles shown in Figure **4**.



5. Intensity of equivalent loads involving W-type vehicles



6. Axle arrangement in N-type vehicles

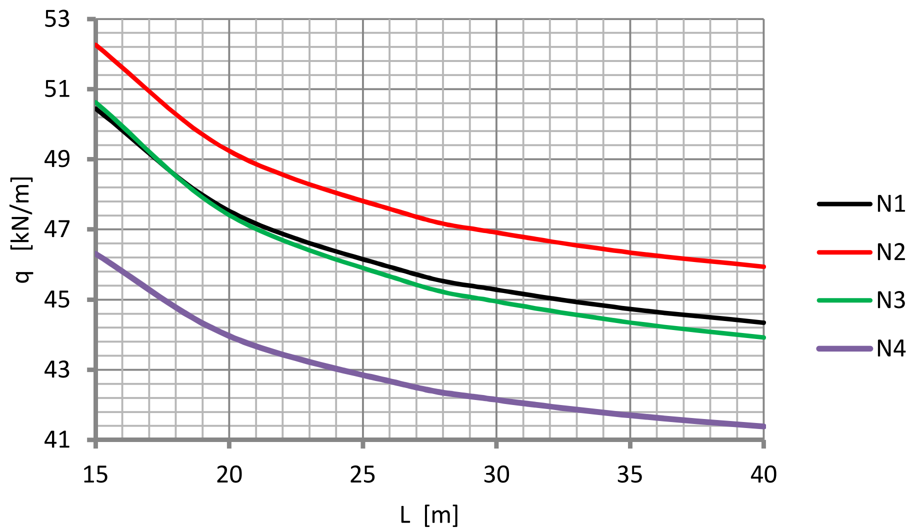
Figure **7** shows the results of calculations analogous to those given in Figure **6**. The highest values of *q* are obtained in the case of car N2, which is the heaviest of the vehicles. Comparing the results from Figures **5** and **7**, higher values of *q* are visible for cars with fewer axles and similar weight to vehicles with five axles. A significant scattering of the graphs is visible. The *q* values from the graphs given in Figures **2**, **5** and **7** are consistent.

Tab. 3. Axle loads in construction vehicles [kN]

Vehicle	P_1	P_2	P_3	Q
N1	96,0	96,0	118,5	429
N2	99,4	99,5	122,8	444,5
N3	89,4	89,4	129,1	437
N4	91,9	91,9	113,6	411

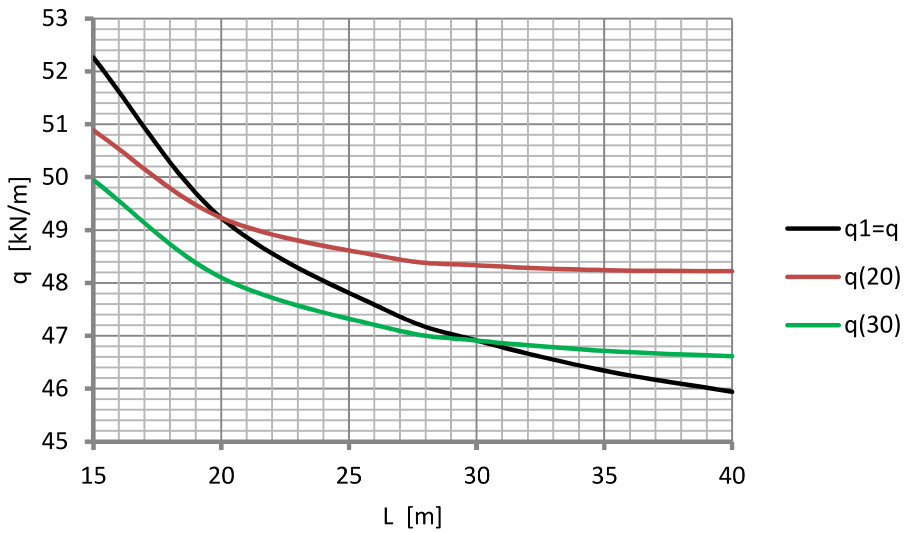
Tab. 4. Geometrical parameters of construction vehicles [m]

Vehicle	a_0	a_1	a_2	a_3	a_4	L_s
N1	1,40	1,95	2,40	1,35	1,10	8,20
N2	1,40	1,95	2,40	1,35	1,10	8,20
N3	1,45	1,85	2,45	1,45	1,35	8,55
N4	1,40	1,40	2,70	1,55	1,35	8,40



7. Intensity of equivalent loads with N-type vehicles

The calculation results presented in Figures **5** and **7** were obtained from the formula (10), i.e., assuming the compatibility of the loads in the congestion and the equivalent impact, i.e., $q_1 = q_2 = q$. Fig. **8** shows the graphs created with the assumption of a constant, L-independent value of $q_1 = q_2$. To determine $q_1 = q_2$, two values were chosen: $L = 20$ m $L = 30$ m. Thus, Fig. **8** shows the consistency of the results obtained at these points. From the graphs given in this figure, the relaxation of the function q(L) can be seen, which means that the equivalent loads generally stabilize at larger spans. This is natural, because, in bridges with large spans, the effect of a standard load in the form of a system of concentrated forces (e.g. K800 vehicle) becomes a supplementary element and not a basic element as in a small bridge[1].



8. Intensity of the equivalent loads with the participation of the N2-type vehicle

The paper omitted the results of analyzes using the general formula (7). It is useful for calibrating lane load factors on a single-way (highway-type) bridge. Then, the values of q_{ik} appearing in EN [10] can be analyzed. The range of possibilities for parametric analysis is very large. A special case occurs when there is an equal proportion $q_1/q_2 = \alpha_1/\alpha_2$.

Passing vehicles on the bridge

On bridges with small spans, more dangerous than the formation of congestion, as shown in Figure **3** are the situations of passing each other by two vehicles going in opposite directions. When vehicles are in motion, for their safety, the distance between them and other cars must be considerable. Thus, it is assumed that there are only two cars on a small bridge structure.

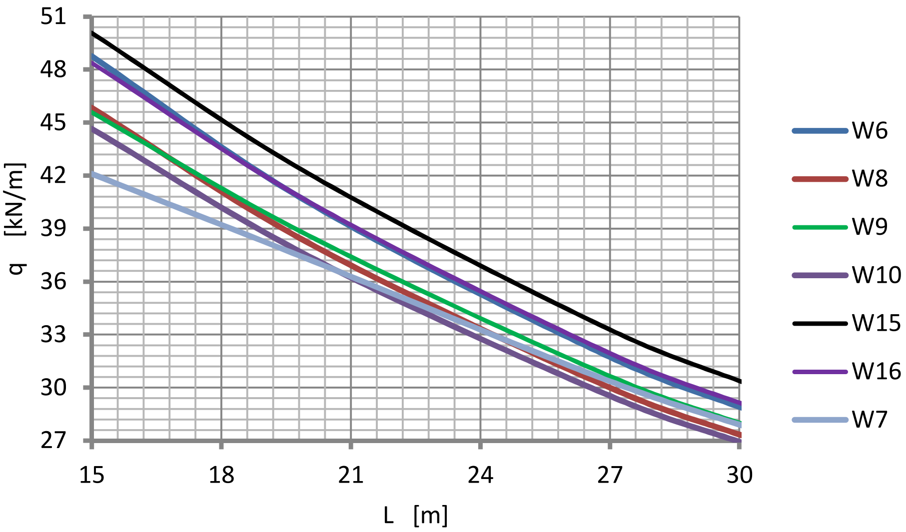
With these assumptions, using the comparative algorithm presented earlier, an equivalent load is obtained

$$q=\frac{8\varphi}{L^2}\sum_{i=1}^{n}P_i\cdot\eta_i=\frac{270-L}{25L^2}\sum_{i=1}^{n}P_i\cdot\eta_i \quad . \tag{11}$$

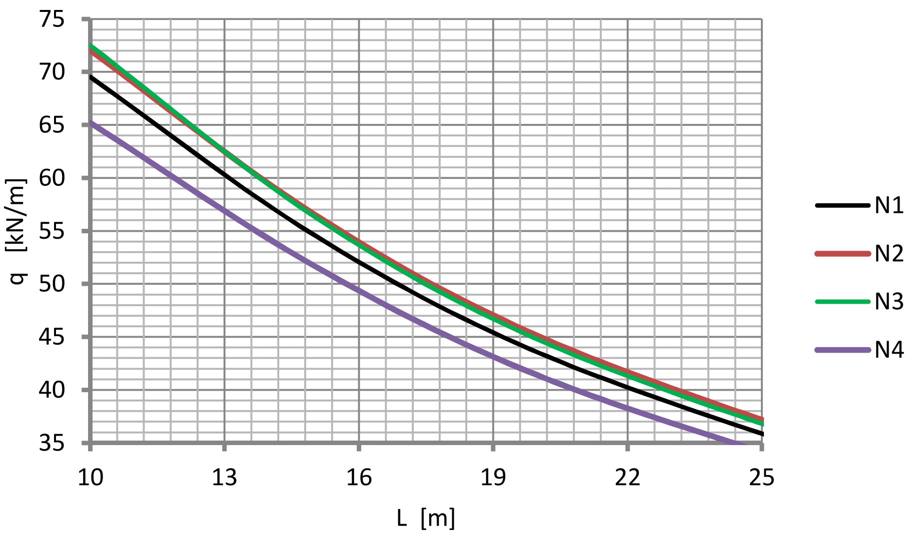
Since both vehicles are in motion, formula (11) includes the dynamic coefficient in the form included in the PN standard [9]

$$\varphi=1{,}35+0{,}005\cdot L=\frac{270-L}{200} \quad . \tag{12}$$

Figures **9** and **10** show the calculation results for the reduced spans of the bridges. This is because, for larger spans, accompanying loads may occur. Therefore, there should be only two cars on the road, assumed in the analysis as the same type and in an unfavorable position, as in Figure **3.**



9. Equivalent load for W-type vehicles



10. Equivalent load for N-type vehicles

m the results given in Fig. **10**, the load on the road lane can be calculated as a surface force. If the width of the carriageway is assumed to be b_j = 3,5 m, the maximum value of q gives the load

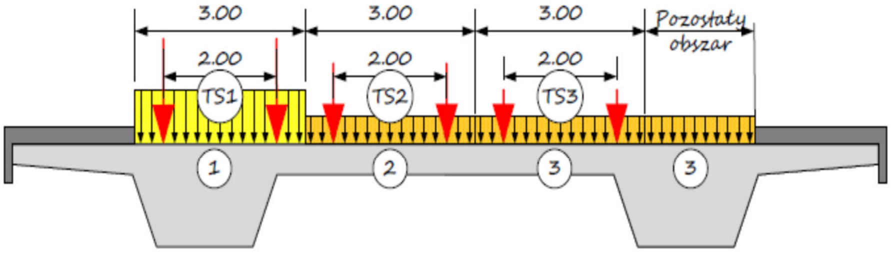
$$p = \frac{q}{b_j} = \frac{72{,}5}{3{,}5} = 20{,}7 \ kN/m^2 \tag{13}$$

The value given above is very large because q depends to a large extent on taking the dynamic action into account. When L = 10 m, formula (12) shows that φ = 1,3. Thus, if the situation of congestion involving two vehicles N2 was considered, q = 72,5/1,3 = 55,8 kN/m is obtained and so a value close to that given in Fig. **7.**

The previously analyzed situation of cars passing each other also applies to the parallel passage of cars going in the same direction, as in the case of overtaking resulting from the normal arrangement of cars on a motorway-type facility.

Bridge design loads

Modern bridges are designed for the passage of heavy vehicles. In the case of applying European standards [10], the diagram of moving loads is given in Fig. **11**. The system of distributed and concentrated loads is similar to the congestion model shown in Fig. **3**. In previous standard recommendations [9], a very heavy vehicle was also used in the form of the K800 tractor. The structures of the bridges were checked for the passage of Stanag 2021 military vehicles weighing 1514 kN or 1023 kN with axle loads of 374 kN and 267 kN, respectively.



Tablica 4.2 – Model Obciążenia 1: wartości charakterystyczne

Położenie	Układ tandemowy TS	Układ UDL
	Obciążenia osi Q_{ik} (kN)	q_{ik} (lub q_{rk}) (kN/m^2)
Pas Numer 1	300	9
Pas Numer 2	200	2,5
Pas Numer 3	100	2,5
Pozostałe pasy	0	2,5
Obszar pozostały (q_{rk})	0	2,5

11. Load diagram adopted in PN-EN 1991-2: 2007

In the case of old, hundred-year-old bridges, the loads were much lower [13]. As design loads from this period, vehicles in the form of a road roller weighing 24 tons and a two-axle car weighing 12 tons were used. As a global load, a uniformly distributed force was used, depending on the span of the bridge $L > 25$ m, with an intensity

$$q = 5{,}25 - \frac{L}{100}\ [kN/m^2] \quad . \tag{14}$$

Thus, the loads were much lower than indicated in Fig. **11**. A very large part of these hundred-year-old bridges is currently in operation.

Summary

The paper investigates the safety of road bridges when loaded to capacity with motor vehicles. Considered in the work is the situation of a full load of bridges occurring during road congestion. The paper presents a model of a simple object, as in Fig. **3**, with a numerical analysis that takes into account the heaviest vehicles on the roads in Poland. As an extreme case, the load from two vehicles on a small bridge was considered. The results of the analyzes were related to the results of measurements made during a traffic jam on a large suspension bridge with a random arrangement of vehicles.

The maximum q values obtained from on-site tests and numerical analyzes using a simple congestion model show a high degree of convergence. Therefore, the intensity of loads from congestion on the bridge in Plock is comparable to the calculation results when the span range applies to average road structures and motor vehicles, as in Figures **4** and **6**. Therefore, the presented results of the parametric analysis may reflect the situation encountered on most road bridges [1].

The paper presents a comparative algorithm used to determine the equivalent load with the general formula (7). It is designed to calibrate lane load factors on a single-way (highway-type) bridge. Then one can analyze the values of q_{ik} occurring in EN [10], as in Fig. **11**. The range of possibilities for parametric analyzes is very large; it has been deliberately omitted in the work. Previously, the probabilistic approach was preferred for bridge safety analyses [13]. This is another work in the field of determining the design loads of bridges in Poland. The issue of a national annex to the EN standard has been discussed for a long time [10]. To achieve this goal, it is necessary to measure the intensity of loads, performed not only on bridges but also on roads [14, 15], because in both structures there are the same vehicles.

Fig. **3** shows the diagram of the concrete structure analyzed in the paper. The comparative algorithm is discussed using the examples of a double-girder span and a plate-beam system. This method of analysis also includes other types of steel bridges with a double-girder structure, e.g., lattice or arch bridges, as shown in Fig. **12**. In the case of a truss bridge, the lines of influence of the axial force in the upper (or lower) chord are of the same shape as the line of influence of bending moments in the main girder of the structure shown in Fig. **3**. When an arch-reinforced beam bridge is analyzed, the result of the analysis also depends on the analyzed internal force and the static scheme of the structure, but strictly on the influence line. This also applies to multi-span beam bridges.

12. Examples of double-girder bridges

Source materials

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