

Peer reviewed paper

# Bridge Network Analysis Program

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## Abstract

Bridge asset management is an important task to maintain the safety of our transportation network. The key activities of management of bridge assets include bridge inspection, analysis, assessment, bridge rehabilitation, and structural monitoring. The bridge analysis and assessment are proactive actions to evaluate the ability of the bridges to cope with heavy vehicle loadings on the networks. Currently oversized and over mass vehicles operate on our aging bridge networks with their mass much heavier than of original design vehicles. Therefore, our bridges will be at risk of failure if we do not check for load carrying capacity. A single bridge can be analysed easily using existing computer software. However, when assessing bridge networks for multiple heavy vehicle loadings, it will be difficult and high risk if a simple approach is used. The Bridge Network Analysis Package is a new computer program that can undertake structural analysis for bridge networks using the Finite Element Method. The package includes (1) Line load analysis, (2) 2D-frame analysis module for box culverts, and (3) 2-D grillage model module. The program can undertake structural analysis for all types of bridge structures including single span, multiple spans, continuous bridge, bridges with drop in span, cantilever bridge, single and multiple cell box culvert structures. In addition, the 2-D grillage module can be used for undertaking detailed bridge analysis; this program can undertake structural analysis for all types of bridge superstructures including concrete, steel, composite and timber. The program can help bridge authorities to rapidly undertake structural analysis, screening, assessment and reissuing of heavy load permits easily, efficiently and economically.

**Keywords:** Bridge Network, The Finite Element method, Line Load Analysis, Grillage Model, Load Rating, Oversize Over Mass Limit.

## 1. Objective

The main objectives of this article are to (1) introduce the Bridge Network Analysis Program, (2) briefly present the methodology used to develop the program and (3) demonstrate the capability of the program in undertaking structural analysis and calculating load rating factors for bridges on the Australian Road Network.

## 2. Background

The majority of existing bridges in Australia were designed for the following historical standard vehicles: MS18, HS20 and T44. In certain conditions, bridges were designed for the Standard Abnormal Vehicles but the configurations of this type of vehicles were not consistent among the State Road Agencies. Only a small number of bridges have been designed for the SM1600, HLP300 and HLP400 loads since the release of AS 5100 in 2004.

The masses and Ground Contact Widths (GCW) of MS18, HS20 and T44 are lighter and narrower in comparison with Over Size Over Mass (OSOM) vehicles operating on our current bridge networks. In order to allow OSOM vehicles to travel safely on existing bridge networks and to minimize bridge deterioration rates caused by such heavy vehicles, the road authorities have enforced heavy load permits.

Generally, the simplest method to assess an existing bridge under a particular vehicle is to compare the load effects caused by that vehicle to those of the original design vehicles using a line load model. This method would be reliable if the compared vehicles have the same GCW as the original design vehicles. However, existing heavy vehicles (including OSOM vehicles) usually have wider GCWs in comparison to the pre-2004 original design vehicles, as mentioned above. Therefore, the transverse live load distribution of the heavy vehicles is likely different from that of the original design vehicles. As a result, using the line load model approach in these circumstances could yield an inaccurate result.

Further steps could be utilised to improve the accuracy of the assessments. This would involve calculating the percentage live load distribution factors on bridge beams using the formulae specified in AASHTO - LRFD Bridge Design Specifications. The percentage live load distribution factors were calculated taking account of the GCWs of the considered vehicles, bridge types and geometry. Therefore, the design actions on critical beams could be more accurately determined. However, the AASHTO load distribution factor is found to be conservative for most bridge configurations [11] and is only applicable for design and detailed assessment for single bridge rather than at network level.

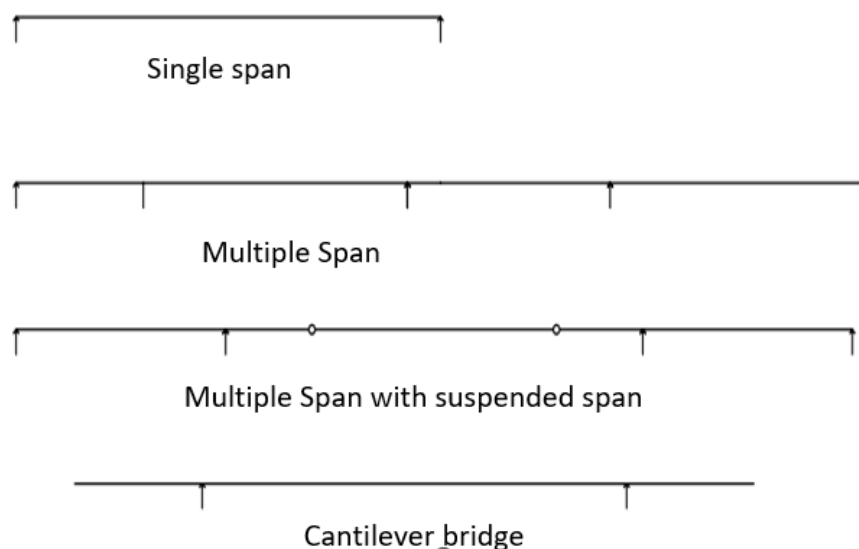
The above method is usually used to screen critical bridges under the considered vehicles at network level due to its simplicity. Then, a more refined analysis such as the 2D/3D grillage or the finite element methods could be utilised to confirm the structural adequacy of the assessed bridges. This step usually requires considerable resources (i.e. engaging experienced bridge engineers to undertake the assessment) and significant amount of time and money. Moreover, load tests can also be used to determine the live load distribution factors of the beam bridges in combination with desk top assessments for certain bridge structures [5]&[6].

It is important to differentiate between new bridge design and bridge assessment. New bridge designs are usually based on standard vehicle configurations under normal conditions. The number of lanes is calculated by dividing the bridge carriage way width to relevant standard lane width. On the other hand, when assessing a bridge for heavy load permits the proposed vehicles can be positioned within the bridge's physical marked lanes. In addition, the OSOM's GCWs are wider than that of the reference vehicles, therefore the live load distribution factors of OSOM vehicles are normally lower across the bridge beams in comparison to the standard design vehicles. Under heavy load permits, the heavy vehicles can be controlled by reducing their speed and positioned in the centre lane. As a result, potential OSOM vehicles can still cross the bridges safely even through their weights are much heavier compared to those of the reference vehicles.

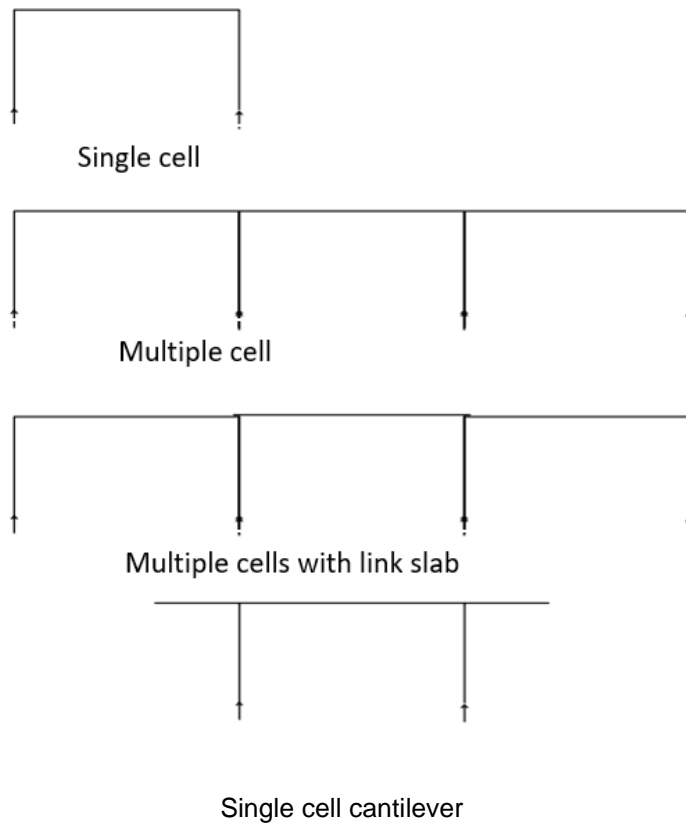
It is estimated that across the national road network, there are over 50,000 bridges and a large number of culverts [1]. Around 25,000 bridge structures are being managed by local councils [9]. In addition, Australia has a large number of registered heavy vehicles [2] and these vehicles need to apply heavy load permits to travel on our road networks. When undertaking bridge assessments for heavy load permits, bridge asset owners usually engage bridge engineers to assess the structure at the Ultimate Limit State (ULS). A Serviceability Limit State (SLS) assessment is often neglected. Normally, overloaded trucks cause more damage on concrete bridge deck structures [7]. The rate of deterioration of bridge networks were found to be related to the bridge's serviceability conditions and this should not be overlooked during an assessment.

To optimise the assessment process for heavy load permits, bridge asset owners in Australian and other countries have put considerable efforts in developing efficient tools. There are available commercial tools that can produce load rating for individual bridges. For assessing multiple bridges at the network level, only few tools have been developed. However, many assumptions have been made to simplify the assessment. Moreover, such tools can undertake structural analysis for simply supported bridge structures only. The most common existing tools are unable to (1) analyse continuous bridges, (2) analyse box culverts and (3) check potential critical locations at different sections along bridge beams. In order to accurately calculate the load effects, as mentioned above, a detailed structural analysis usually utilises grillage model to determine percentage live load factors (PLDFs) for both bending moment and shear force. The PLDF will be then multiplied with the total load effects obtained using a line load model to determine load effects on each individual beam. In certain bridge configurations (curved bridges or bridges with skew angles), and a vehicle with various ground contact then it would be challenging to accurately determine the PLDFs. Another limitation of the available tools is that they can only provide the maximum values of each load effect without providing the related coexisting load effects. It is also critical to note that bridge and culvert structures should be assessed for both the ULS and SLS, as mentioned above.

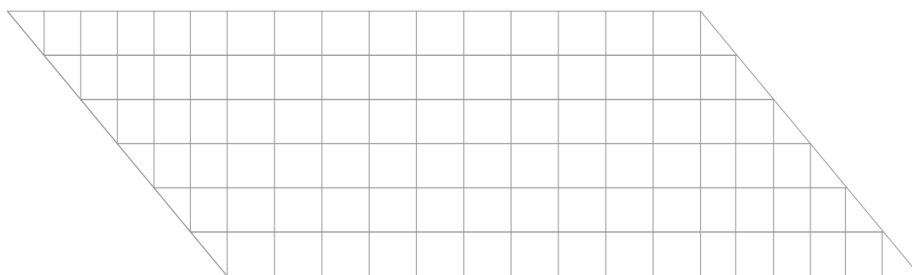
To address all the above issues, a new computing program has been developed using the Finite Element Method. The program includes three modules: (1) the line load analysis, (2) 2D-frame analysis, and (3) 2D-grillage analysis. Figures 1, 2 and 3 below present the typical structural configurations included in each module, respectively.



**Figure 1** Line load analysis module



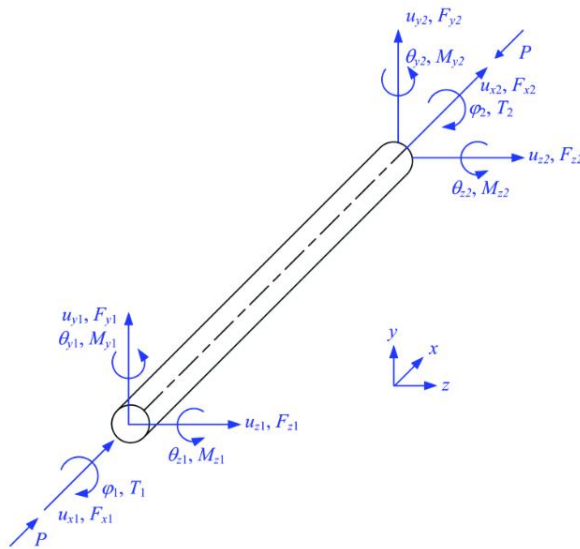
**Figure 2** 2D-frame analysis module for box culverts



**Figure 3** 2D-grillage analysis module

### 3. Bridge Network Analysis Program

The Bridge Network Analysis Program has been developed by the author with the purpose of undertaking structural analysis for multiple bridges at the network level. The programming language used is C Sharp (C#). The Finite Element Method (FEM) was employed in the above modules. Direct stiffness matrix was used to determine node displacements (rotations and translations) of members. Figure 4 shows a three-dimension beam element in the space with 12 degrees of freedoms at two (2) ends; symbol  $u$  and  $\theta$  are linear displacements and angular displacements about x-axis, y-axis, and z-axis, respectively.



**Figure 4.** End displacements and design actions in 3D beam member

Because the program has only been developed for (1) Line load analysis, (2) 2D - frame analysis and (3) 2D- grillage analysis, the number of degrees of freedom at each node is reduced, optimizing the use of resource for execution of the program (Table 1).

Module	Displacement	Load effect
(i) Live Load analysis	$(u_{y1}, \theta_{z1}, u_{y2}, \theta_{z2})$	$(M_{z1}, F_{y1}, M_{z1}, F_{y1})$
(ii) 2D frame	$(u_{x1}, u_{y1}, \theta_{z1}, u_{x2}, u_{y2}, \theta_{z2})$	$(P, M_{z1}, F_{y1}, P, M_{z1}, F_{y1})$
(iii) 2D- Grillage model	$(\phi_1, u_{y1}, \theta_{z1}, \phi_2, u_{y2}, \theta_{z2})$	$(M_{z1}, F_{y1}, T_1, M_{z2}, F_{y2}, T_2)$

**Table 1:** the Degree of freedom for the Bridge Network Analysis program

The detailed computing process to obtain displacements and load effects is beyond the scope of this paper and can be found in many FEM academic textbooks.[4]&[9]

#### 4. The features of the Bridge Network Analysis Program

One distinctive feature of the program is that it can be used for structural analysis of multiple bridges (up to hundreds of structures) at the network level in a short time period. The program is developed to manipulate bridge data with primary bridge database via Structured Query Language (SQL).

Figure 5 shows a working chart for processing heavy load permits using the program. The primary bridge database consists of normalized structural data tables under Boyce -Code Normal Form (BCNF) for eliminating of redundance. The primary bridge database includes logical tables storing travel routes, bridge locations, bridge geometries, bridge properties and vehicle configurations. There are a number of professional database providers that can be used to store the primary bridge database such as Microsoft SQL Server, Oracle, etc. By using the professional database structure providers, the primary bridge database is able to build a large number of bridge configurations. Figure 6 shows a list of tables included in a typical bridge database.

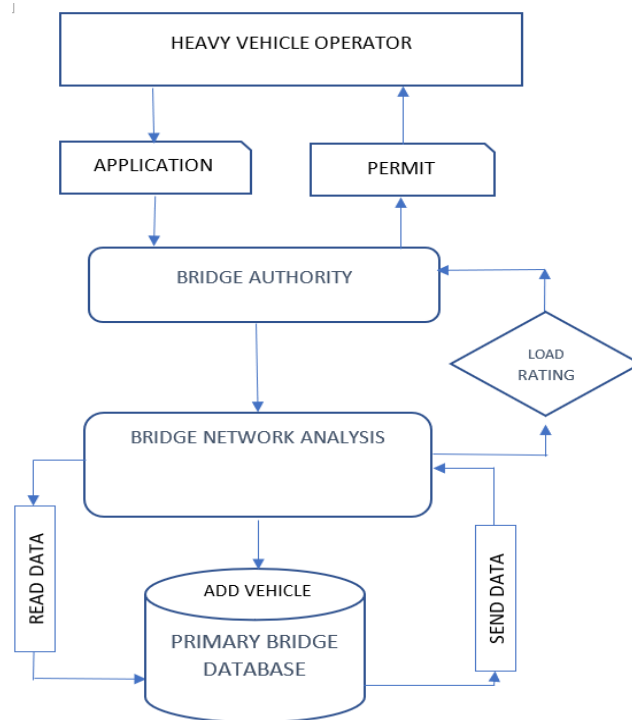
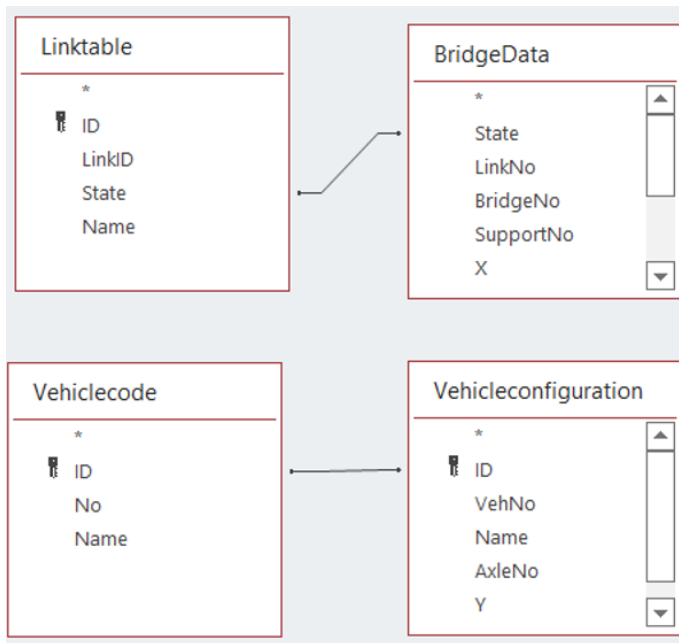


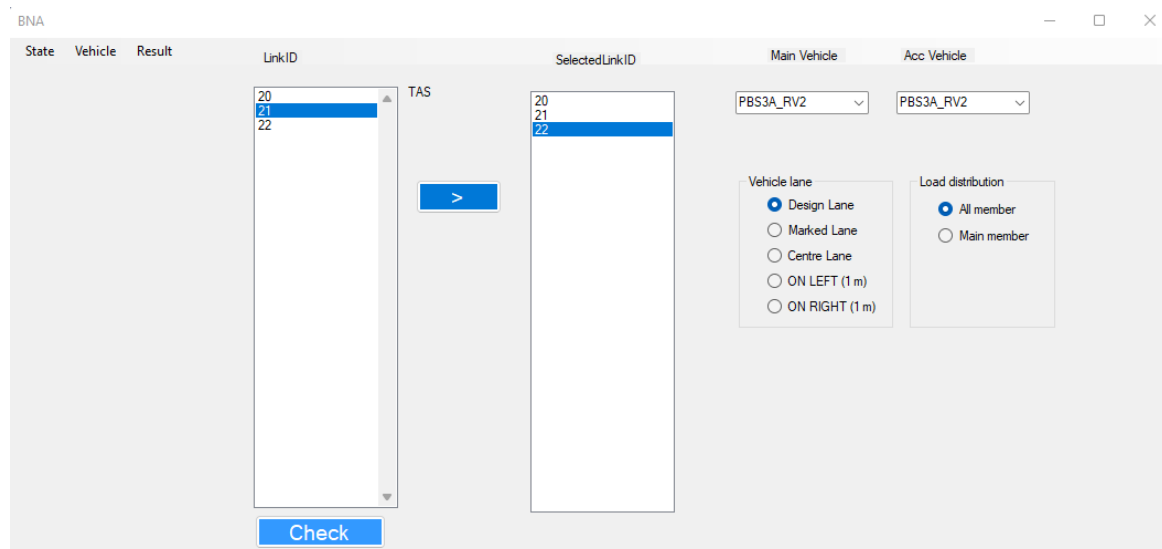
Figure 5 The Bridge Network Analysis Process



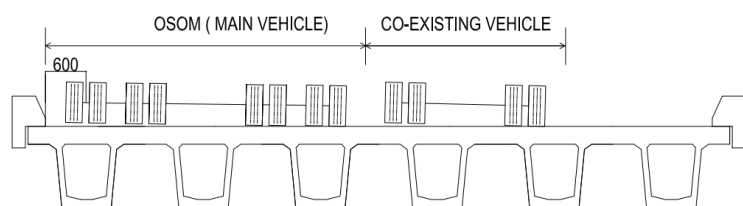
**Figure 6.** Typical primary bridge database tables

There is a special dynamic SQL that was built in the program using C# in Visual Studio for reading data tables from the primary bridge database.

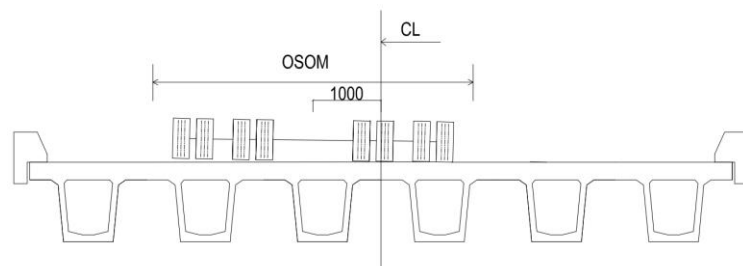
When assessing for a heavy load permit, heavy vehicle configuration data can be input directly to the entry form, or it can be imported from an Excel file. The heavy vehicle configuration could be added to the primary bridge database for the future use. The program can display the information of a main vehicle and one co-existing vehicle as shown on Figure 7. The program can assess the vehicle(s) under three different lane cases: design lane, marked lane and bridge centreline. Figure 8 and Figure 9 show the locations of the vehicle(s) in the design lane and bridge centreline cases, respectively.



**Figure 7.** User interface of 2D-Grillage analysis module



**Figure 8** Vehicle in design lane case



**Figure 9** Vehicle in the bridge centreline case

The program also allows users to select travel routes for a heavy load permit at national level or local road networks. When routes are selected, the program will automatically assign bridges to the temporary memory through the dynamic SQL. After that, the program will undertake structural analysis and calculate the load rating factors. Depending on the order of structural analysis, the users can choose a module among the line load analysis, 2D-frame analysis or 2D-grillage analysis modules. For the line load analysis and 2D-frame modules, the program can analyse a large number of vehicles that cross multiple bridges with different bridge types and configurations in the selected routes within a few minutes. The 2D-grillage module is the most powerful module of the program, with some noteworthy features presented below:

- It is able to automatically calculate the number of lanes for the nominated bridges located on the selected routes in accordance with Clause 11.3 of AS 5100.7-2017 (+A1).
- It has the capability to generate the travel paths for bridges with straight and curve alignments, with and without skew angles.
- It can undertake structural analysis for the most common types of bridge superstructures including steel, composite, timber, normal reinforced concrete, pre-tensioned and post-tensioned concrete bridges.
- It can automatically retrieve section properties of members including second moment of areas, section areas, torsional constants, material properties that are stored in the primary bridge database. Such information can be inputted manually from other commercial structural analysis programs such as SpaceGass and Microtran, etc.
- It is able to calculate the distribution of wheel loads to different grillage members under two cases: wheel loads are distributed to (1) all members and (2) the primary beams. The program can analysis for heavy vehicles with their number wheel exceed 500 wheels.
- It can assess a main vehicle and a coexisting vehicle on the bridges taking into account accompanying lane factors.
- It can generate enveloped load effects at the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) for (1) maximum bending moments with coincident shear forces and torsional moments, (2) maximum shear forces with coincident bending moments and torsional moments, and (3) maximum torsional moments with coincident shear forces and bending moments. The program can also calculate the support reaction at a node and its coincident reactions at other nodes.
- The 2D-grillage module is capable to calculate the bridge Rating Factors (RF) using the below formula:

$$RF = \frac{\phi R_u - S^*}{R_{LL}^*}$$

- Where:
- $\phi R_u$  = the total ultimate structural capacities of a member. If the bridge has no information on the actual capacities, the total capacity  $\phi R_u$  is assumed to be based on the original design vehicles (MS18, T44 or HS20).
- $S^*$  = total other load effects due to dead loads, thermal loads, creep and shrinkage effects, differential settlement and secondary effects from prestressing.

The final load rating factors of the bridges on the selected routes can be presented in the report form within the program or can be exported to Excel file or Google Map API.

Table 2 presents an example of the assessment results of a bridge assessed using the 2D-grillage module.

State	Link	Bridge no	Beam No	Node No	ØMu-M'dl	M'II(KNm)	ØVu-V'dl	V'II(KN)	RF_M	RF_V
TAS	21	12	2	29	6	0	565	558.506	99	1.01
TAS	21	12	2	30	1345	751.998	561	552.96	1.79	1.01
TAS	21	12	2	31	1425	1358.178	551	461.904	1.05	1.19
TAS	21	12	2	32	2005	1896.256	455	424.944	1.06	1.07
TAS	21	12	2	33	2405	2351.658	425	390.864	1.02	1.09
TAS	21	12	2	34	2875	2722.852	375	359.612	1.06	1.04
TAS	21	12	2	35	3005	2931.684	350	343.006	1.03	1.02
TAS	21	12	2	36	3205	3165.594	337	320.546	1.01	1.05
TAS	21	12	2	37	3405	3361.32	304	297.714	1.01	1.02
TAS	21	12	2	38	3655	3520.464	294	272.052	1.04	1.08
TAS	21	12	2	39	3785	3628.174	253	247.344	1.04	1.02
TAS	21	12	2	40	4015	3694.266	227	214.072	1.09	1.06
TAS	21	12	2	41	4205	3727.458	204	190.874	1.13	1.07
TAS	21	12	2	42	4239	3724.79	180	169.104	1.14	1.06
TAS	21	12	2	43	4428	3731.764	186	-180.168	1.19	1.03
TAS	21	12	2	44	4239	3692.778	227	-203.75	1.15	1.11
TAS	21	12	2	45	3895	3616.598	239	-230.772	1.08	1.04
TAS	21	12	2	46	3531	3483.822	266	-259.208	1.01	1.03
TAS	21	12	2	47	3455	3311.842	295	-289.338	1.04	1.02
TAS	21	12	2	48	3105	3092.188	336	-322.638	1	1.04
TAS	21	12	2	49	3007	2830.522	375	-372.01	1.06	1.01
TAS	21	12	2	50	2821	2545.82	437	-420.562	1.11	1.04
TAS	21	12	2	51	2317	2239.91	476	-463.286	1.03	1.03
TAS	21	12	2	52	1985	1877.028	514	-502.584	1.06	1.02
TAS	21	12	2	53	1545	1444.116	560	-543.536	1.07	1.03
TAS	21	12	2	54	1005	976.466	615	-605.082	1.03	1.02
TAS	21	12	2	55	455	430.876	675	-661.258	1.06	1.02
TAS	21	12	2	56	10	-3.47	607	-596.488	2.88	1.02
TAS	21	12	3	57	8	1.31	645	635.184	6.11	1.02
TAS	21	12	3	58	805	854.654	615	608.2	0.94	1.01
TAS	21	12	3	59	1425	1467.91	515	479.854	0.97	1.07
TAS	21	12	3	60	2005	1958.162	425	415.152	1.02	1.02
TAS	21	12	3	61	2405	2359.248	392	375.746	1.02	1.04

Table 2 Example of results of a bridge assessed using 2D-grillage module

## 5. Implementation

The line load module has been used for undertaking structural analysis and quality assurance (QA) of 500 single span bridges with 5500 special purpose vehicles (SPV). It took the author only 10 days to perform the structural analysis of the whole package including the initial setup and data input.

In addition, both the line load and 2D-frame modules were used to undertake the Tier 1- bridge assessment for 30 structures consisted of simple and continuous bridge structures, and box culverts with 111 vehicle configurations for The NHVR's Strategic Local Government Asset Assessment Project (SLGAAP). The analysis, including the provision of live load factors, was completed within 3 hours.

The 2D-grillage module was used to undertake testing for detailed structural analysis and assessment of several bridges on a specific route. There are eight (8) bridges: four (4) concrete bridges, two (2) steel concrete composite bridges without skew angle, and two (2) simply supported bridges with a skew angle of 30 degree. Some of the bridges are single-span, others possess multiple spans with and without internal hinges. Multiple vehicle lanes were also considered in the analysis. The test showed that the program was able to accurately calculate the load ratings at different sections along the bridge beams (defined by the number of nodes in the grillage models). The running time for the structural analysis took less than one (1) minutes to produce the load ratings for all the considered bridges.

## 6. Conclusion

This program will help bridge asset owners at state and local government levels in assessing special heavy load permit applications for multiple bridges on the nominated routes with minimal involvement of bridge engineers.

The program has demonstrated capability to undertake structural analysis of multiple bridges in a very short time. The program can be used for screening (using line load models) and/or detailed bridge assessments (using 2D-grillage model).

The program would be updated to automatically identify bridges that are in specific routes, based on the bridge database provided by the relevant road authorities. The required bridge data, unless they could be linked directly, need to be input into the program. The program will then undertake structural analyses using line load and/or 2D-grillage modules to calculate load effects due to considered vehicles. Load ratings could be calculated by comparing the considered vehicles to the original design vehicles or directly comparing the load effects due to the considered vehicles to the actual bridge element capacities (if available).

Another feature of the program which is being developed will enable interaction with Google Map Application Programming Interface (API). With this development, online users can assess multiple bridge networks using the HTTP protocol.

It is also the author's intention to further develop the program's capability for undertaking more complex structural analyses such as space frame and truss bridges.

## 7. Recommendation

Bridge asset owners should consider using this new efficient assessment tool for assessing their bridges at network level.

The bridge database should be stored in proper database management software such as Microsoft SQL server, Oracle rather than improper tools such as Microsoft Excel (or even Microsoft Access), etc. This will help increase data integrity and security, minimize data inconsistency, speed up data access and provide many more benefits of big data management.

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