TRUCK SIZE AND WEIGHT ANALYSIS FOR THE DEVELOPMENT OF A EUROPEAN BRIDGE FORMULA

by

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ABSTRACT

The research analyzes the bridge load stress effects resulting from international bridge formulae and truck size and weight regulations in Europe. This is done with a view to identifying issues that may need to be considered in the development of a European Bridge Formula (EUBF) conforming to European Directive truck configurations for the regulation of truck size and weight limits associated with international travel between European Union (EU) member states.

The level of efficiency of bridge formulae vary depending on the design criteria used in the development of the formula, the compatibility to the jurisdiction's infrastructure and truck fleet characteristics, and the method of implementation as part of the regulation and by operators in the trucking industry. The EUBF should limit imposed critical bending moment and shear stresses on single and continuous span bridges of varying lengths (5, 20, and 50 metres) in accordance to design live loads specified in the Eurocode. The analysis of bridge load effects imposed by European Directive truck configurations in this research, provide the basis for the development of a EUBF.

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1. INTRODUCTION

1.1. THE RESEARCH

The research analyzes the bridge load stress effects resulting from international bridge formulae and truck size and weight regulations in Europe. This is done with a view to identifying issues that may need to be considered in the development of a European Bridge Formula (EUBF) conforming to European Directive truck configurations for the regulation of truck size and weight limits associated with international travel between European Union (EU) member states.

A “bridge formula” is a mathematical equation designed to protect bridges by determining the maximum weight allowed on any series of consecutive axles as a function of axle spacing, and in some cases the number of axles. Bridge formulae provide a method for the regulation of truck weights while ensuring the sustainability of infrastructure by allowing vehicle configurations that have an acceptable load effect on structures.

1.2. BACKGROUND AND NEED

Truck size and weight are regulated differently in every country with the primary purpose of protecting highway infrastructure from excessive damage (TRB, 1990). The Gross Vehicle Weight (GVW), axle loads, number of axles, length of vehicle, and inter-axle spacing determine the level of impact of the truck-related live load induced on bridges and pavements as a result of truck operations. The regulations concerning these parameters determine truck characteristics which in turn impact infrastructure, truck productivity, transportation safety, efficiency, the economy, and the environment. Increased efforts are being placed to achieve an appropriate balance between truck productivity and infrastructure design, operation, and maintenance to allow increased utilization of the bridge capacities while ensuring reasonable service life of roadway systems (Moshiri et al., 2011 & Jacob et al., 2010).

Typically truck sizes and weights are determined by prescriptive methods where gross vehicle and axle weight limits and vehicle dimensional limits are fixed, with little flexibility allowed in vehicle design. In the last three decades there has been a move towards performance-based standards where sizes and weights are regulated based on the vehicle's performance requirement and interaction with the traffic and infrastructure. This movement has been specifically directed at promoting safe and efficient freight transportation while reducing road infrastructure wear (York & Maze, 1996). A performance-based standard in its pure form regulates truck size and weight based only on performance measures, such as impact on safety and the environment, load effect imposed on infrastructure, traffic impacts, vehicle productivity, and geometric effects (Sweatman et al., 1999). This is particularly the case in Australia and New Zealand.

A “bridge formula” can be a variation of performance-based standards, where it regulates parameters that are related to the performance of the vehicle in terms of the load effect imposed on bridges and pavements. These formulae are designed to protect bridges by determining the maximum weight allowed on any series of consecutive axles as a function of the extreme axle spacing and the number of axles within the considered axle group in order to limit the imposed stresses on bridges. Bridge formulae provide an efficient method to help with the regulation of truck weights while ensuring the structural integrity of the infrastructure by allowing vehicle configurations that have an acceptable effect on structures. Several countries, including the U.S., Canada (Ontario only), Mexico, South Africa, Australia, and New Zealand, limit the weights of heavy vehicles through a bridge formula. The most well-known and studied bridge formula is the

Federal U.S. Bridge Formula B (BFB) that has been regulating truck size and weight on the U.S. Interstate highways since 1974 (TRB, 1990).

Currently, truck size and weight limits of European Union (EU) member states are regulated by prescriptive measures for international travel through the European Council Directive 96/53/EC (European Union, 1996). However, higher weights may be allowed by individual countries for national travel. The difference in national weight limits across EU countries and the increasing demand for larger and heavier vehicles brings the need to ensure the structural integrity and service life of bridges. A bridge formula allows for future truck size and weight evolutions over a long-term period, while preserving the existing stock of bridges, designed with past and current loading codes.

Based on previous research there is a need to develop and implement a European Bridge Formula for the regulation of truck sizes and weights in Europe for international travel among EU member states. This research will help guide the development of a European Bridge Formula and will contribute new knowledge for countries which currently apply a bridge formula to regulate truck weights.

1.3. OBJECTIVES AND SCOPE

The specific objectives of the research are to:

- Understand previous research regarding bridge formulae and their impacts on the truck fleet.
- Identify and characterize existing bridge formulae.
- Compare the different international bridge formulae in terms of level of restrictiveness of allowable loads and load effects on bridges.
- Understand the European truck fleet for the development of a European Bridge Formula.

- Analyze stress effects imposed by practical European truck configurations on single and continuous span bridges of varying span lengths.
- Identify issues that may need to be considered in the development of a European Bridge Formula.

The scope of this research is limited to:

- Only considering maximum load effects of single truck crossings, therefore not taking into account the effects of possible side by side loading of trucks.
- Using theoretical influence lines for single and continuous span bridges of 5, 20, and 50 metre span lengths.
- The analyzed critical load effects of: (1) bending moment at mid-span of single span bridges, (2) shear force over the support of single span bridges, and (3) bending moment over the support (i.e. pier) of continuous two span bridges.
- The European Union (EU) member states, all of which comply with the European Directive 96/53/EC for truck size and weight limits and the Eurocode for structural design standards. The EU states up to year 2011 are: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and United Kingdom. (Europa, 2011)

1.4. APPROACH

The research consists of three steps:

1. Conduct of a comprehensive literature review of existing bridge formulae based on research published in the last 50 years to identify the methodologies used for the

development of bridge formulae and issues or limitations associated with their development or implementation. The levels of restrictiveness of the formulae are also compared in terms of allowable loads and imposed bending moment stresses on single span bridges.

2. Assessment and comparison of maximum stress load effects of different European trucks on single and continuous span bridges of 5, 20, and 50 metre span lengths at critical stress locations of mid-span and over the support. The analysis of the vehicle-bridge interaction is conducted using the ‘Pollux’ software developed by the French Institute of Sciences and Technologies for Transportation, Development, and Networks (IFSTTAR), formerly Laboratoire Central des Ponts et Chaussées (LCPC), while on site at the lab in Paris, France. Pollux input requirements are truck characteristics, including dimensions and weights, and theoretical bridge influence lines.

3. Identification of issues that may need to be considered in the development of a European Bridge Formula used for the regulation of truck size and weight limits associated with international travel between EU member states.

1.5. THESIS ORGANIZATION

The thesis consists of five chapters. Chapter 2 provides the findings of a comprehensive literature review to identify and describe existing international bridge formulae and identify potential issues arising from the development and implementation of bridge formulae. This chapter also provides background on bridge formulae and bridge design concepts, methods, and vehicles (live load models), describing factors relevant to the development of bridge formulae.

Chapter 3 describes the truck size and weight regulations in Europe to understand the need and criteria for the development of a European Bridge Formula.

Chapter 4 outlines the research methodology and provides results for the comparison of international bridge formulae and analysis of truck size and weight data as it relates to the potential development of a European Bridge Formula.

Chapter 5 provides conclusions and recommendations for future research in this field.

1.6. THESIS TERMINOLOGY

For purposes of this research, the following is a list of definitions for terms used throughout this thesis.

- *Bridge formula:* A mathematical equation that determines the maximum allowable weight on any series of consecutive truck axles as a function of the truck configuration parameters including axle spacing and number of axles.
- *Overstress:* The extent to which the design stresses in a bridge are exceeded due to extreme loading events (TRB, 1990 and US DOT, 2000).
- *Fatigue:* The cumulative damage caused by repetitive loading, which can cause cracks or ruptures of key elements of the structure (TRB, 1990).
- *Bending moment stress*: The rotational tendency caused by forces on a beam and resistance to the force by the beam connection (i.e., support) or material properties (U.S. DOT, 2000). It is measured as a force multiplied by a distance with the unit of tonne.metre in this research.
- *Shear stress: "*The tendency for a portion of a structural beam to slide or shear laterally relative to another portion" due to vertical forces and reactions at supports (Codecogs, 2011).

- *Aggressiveness ratio:* The ratio of the maximum bridge load effect imposed by a truck to the maximum bridge load effect imposed by a reference truck. The reference truck in this research is the European five-axle reference vehicle. (Jacob et al, 2010)
- *Wheelbase:* The distance between the centres of the first and last axles of an axle group on a vehicle, also referred to as inter-axle spacing. The outer wheelbase refers to the distance between the centres of the front and rear axles of a vehicle.

2. LITERATURE REVIEW

This chapter provides the findings of a comprehensive literature review to identify and describe existing international bridge formulae and identify potential issues arising from the development and implementation of bridge formulae. This chapter also provides background on bridge formulae and bridge design concepts, methods, and vehicles (live load models), describing factors relevant to the development of bridge formulae.

2.1. DESCRIPTION OF LITERATURE SEARCH

A comprehensive literature review was conducted of research published in the last 50 years to identify existing international bridge formulae, the methodologies used for the development of bridge formulae, and issues or limitations associated with the development or implementation of the formulae. The literature search included a variety of data and information sources: (1) research periodicals and journals; (2) readily available papers and textbooks; (3) conference proceedings; (4) special interest groups; (5) special government reports; and (6) documents on the World Wide Web. The search included the agencies, library catalogues and resources shown here:

Special Library Catalogues

- Transportation Research Information System (TRIS)
- ELSEVIER

Research Centers

- Laboratiore Central des Ponts et Chaussees
- University of Michigan Transportation Research Institute
- University of Manitoba Transport Information Group
- Transport Engineering Research New Zealand (TERNZ)
- Texas Transportation Institute
- University of Texas Center for Transportation Research
- Iowa State University Center for Transportation Research and Education
- Council of Scientific and Industrial Research

Government Agencies

- U.S. Federal Highway Administration
- California Department of Transportation
- Austroads
- National Transport Commission Australia
- Transport Republic of South Africa
- Organisation for Economic Cooperation and Development International Transport Forum

Scientific Journals and Conference Proceedings

- Transportation Research Board
- Canadian Society for Civil Engineering
- American Society of Civil Engineers
- International Symposium on Heavy Vehicle Transport Technology

2.2. BRIDGE FORMULA DEFINITION

A bridge formula is a mathematical equation that determines the maximum allowable weight on any series of consecutive truck axles as a function of the truck configuration parameters including axle spacing and number of axles. It is a method used to regulate truck size and weight while ensuring the sustainability of infrastructure. The formulae are designed to protect bridges and highway infrastructure by limiting the amount of overstress imposed on the infrastructure (TRB, 1990).

2.3. IMPORTANCE OF BRIDGE FORMULAE

There is an increasing demand for higher truck size and weight limits in order to allow improved freight productivity, reduced environmental impacts, lower vehicle operating costs, and potentially reduced truck traffic volume. However, a concern regarding increasing truck weights is the impact on infrastructure due to the increased loads and imposed stresses (TRB, 1990).

Bridge formulae are designed to protect bridges from excessive overstress by limiting the concentration of loadings placed on them, based on assumptions about the amount by which the design stresses can be safely exceeded for different types of bridges. Bridge formulae link allowable vehicle weights to vehicle axle configurations, reflecting the fact that the amount of imposed bridge stresses depends on vehicle axle group weights and length over which this weight is distributed. The maximum stress imposed by increasing vehicle loads can generally be reduced by distributing the load over a longer length (i.e., axle group spacing) and to a lesser extent the number of axles. (Battelle, 1995 & Austroads, 1994)

There has also been the trend to move towards performance-based standards where vehicles are not solely restricted to fixed weights and dimensions; rather more flexibility is allowed in the truck configuration design. A bridge formula can be a component of performance-based standards, which it regulates parameters related to the performance of the vehicle in terms of the load effects imposed on bridges.

2.4. BRIDGE DESIGN OVERVIEW

Bridge formulae are designed to limit the amount of overstress imposed on bridges relative to bridge design stresses (Battelle, 1995) therefore bridge design load models can be the basis of developing bridge formulae. Understanding certain of the fundamentals of bridge design and the evolution of bridge design methods can help in designing a bridge formula suitable for a jurisdiction’s bridge stock.

2.4.1. Bridge Design Concepts

A bridge must be designed to support the various loading demands it may encounter throughout its service life. These include dead loads (the weight of the bridge itself), live loads (the weights of vehicles using the bridge), wind, seismic loads, and thermal forces. The relative importance of these loads may vary depending on the type of materials used in construction, anticipated traffic, climate, and environmental conditions (TRB, 1990).

When evaluating the effects of vehicular live load on bridges, two bridge responses are considered: overstress and fatigue. Overstress is when the design stresses in a bridge are exceeded due to extreme loading events, which may lead to severe damage. Fatigue is the cumulative damage caused by repetitive loading, which can cause cracks or ruptures of key elements of the structure. (TRB, 1990)

When designing for overstress, the bridge capacity is governed by the likelihood of a critical load event of multiple truck presence with unfavourable dynamic and load effect conditions. To account for the critical load event as well as the uncertainties associated with the construction material, environment, occurrence of overweight loading (either illegal or through permits), and the possibility of increase in legal loads during the design life of the structure, the load model (design vehicle) used for bridge design is magnified with a factor of safety (i.e. load factors). The factor of safety is selected so that there is only a very small probability that a loading condition that exceeds load capacity will be reached within the bridge's design life (TRB, 1990). The probability of failure of a structure can be reduced by increasing its design strength, which leads to a higher capital cost (Mufti et al., 1996).

Influence lines are used to calculate the imposed stresses of live loads on different bridge types at critical locations on a bridge. "An influence line for a given function, such as a reaction, axial force, shear force, or bending moment, is a graph that shows the variation of that function at any given point on a structure due to the application of a unit load at any point on the structure." (Fanous, 2000)

2.4.2. AASHTO Bridge Design Methods and Vehicles

Design theory and practice have evolved significantly due to increased understanding of structural behaviour and loading patterns (Caltrans, 2011). The margins of safety used in bridge design have been reduced over the years with the development of new design procedures and computer-aided engineering and design allowing more precise analysis of load effects (Battelle, 1995). In addition to bridge design methods, bridge design loads have also evolved over the past 60 years to reflect the heavier truck populations. When comparing load models, it is necessary to consider the design vehicle as well as the live load factors which further increase the effective load effects on bridges. (Fu et al., 2003)

The evolution of bridge design is evident in the U.S. bridge design methods. The American Association of State Highway and Transportation Officials (AASHTO) publish national codes and specifications for design and construction of highways and bridges throughout the United States (AASHTO, 2011). Prior to 1970, the sole design philosophy was allowable stress design (ASD); in early 1970 the load factor design (LFD) philosophy was introduced. Reliability-based and probability-based load and resistance factor design (LRFD) philosophy was introduced in 1994 (Caltrans, 2011), and continues to be used with the 6th edition published in 2012.

The AASHTO Standard Specifications for Highway Bridges was developed in 1931, where the allowable stress design (ASD) method was specified. The ASD approach uses factors of safety to ensure that the stresses developed in a structure due to service loads do not exceed the elastic limit (i.e., yield strength) of the structure, where beyond this limit permanent deformation occurs (Caltrans, 2011). A factor of 0.55 is applied to the yield stress to reduce the full potential capacity based on the limiting material stress and provide a safety margin. This limit is referred to as the inventory or design stress level. (TRB, 1990)

The AASHTO Standard Specifications for Highway Bridges published in 1944 specified three types of vehicle loading patterns: the H truck configuration, HS truck configuration, and lane loading. The H truck configuration resembles a straight truck with two existing types: H15 and H20. The H15 design vehicle has a gross vehicle weight (GVW) of 13,608 kg (30,000 lb or 15 tons), consisting of two theoretical axles with the front axle weighing 2,720 kg (6,000 lb) and the rear axle weighing 10,880 kg (24,000 lb). The H20 design vehicle, shown in Figure 1, has a GVW of 18,144 kg (40,000 lb or 20 tons) with a 3,630 kg (8,000 lb) front axle and 14,520 kg (32,000 lb) rear axle.

The HS truck configuration represents a semitrailer truck with three axles and also involves two truck types: HS15 and HS20. The HS15 truck has an extra axle of 10,880 kg (24,000 lb) and the HS20 truck, shown in Figure 2, has an extra axle of 14,520 kg (32,000 lb). The gross vehicle weights are 24,490 kg (54,000 lb) and 32,670 kg (72,000 lb) respectively. The rear axle spacing can vary from 14 to 30 feet to determine the maximum moment created for continuous spans.

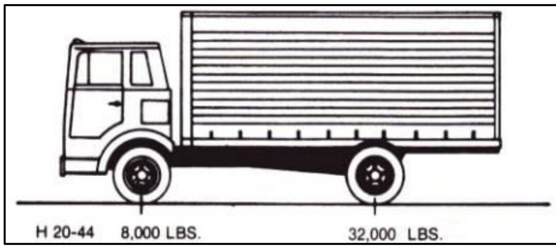


Figure 1: H20 design truck specified by AASHTO
(Pierce et al., 2005)

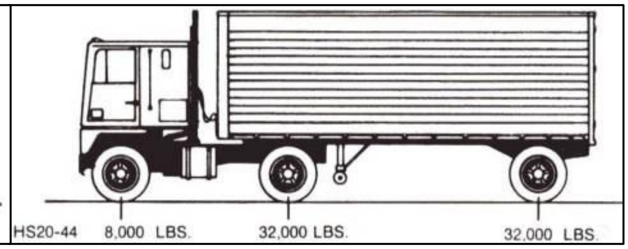


Figure 2: HS20 design truck specified by AASHTO
(Pierce et al., 2005)

The third type of loading is the uniformly distributed lane load which represents a queue of H15 single trucks with an H20 truck in the middle. This type of loading is crucial to consider for long span bridges where slow moving vehicles can cause a queue of vehicles, creating heavier loading relative to high speed vehicles with greater headways. To take this effect into account, the HS20 vehicle is accompanied by a lane load of 952 kg/linear metre (Woodrooffe, 2010).

The increase in truck size and weight limits over the years has created the need for a heavier design vehicle loading. This resulted in some states increasing the HS20 vehicle loading to an HS25 design vehicle which consists of a 25 percent larger loading (TRB, 1990). With the changing truck fleet configurations, the double trailer HSS vehicle was introduced with a GVW of 59,670 kg for an HSS 25 and 71,600 kg for an HSS 30 design vehicle compared to the maximum 62,500 kg operating double trailer trucks.

In the early 1970s, AASHTO updated the specifications with the Load Factor Design (LFD) standards, which applied magnification and reduction factors to the loads and member resistance respectively, rather than applying one overall factor of safety. The load factors varied depending on the engineer's ability to predict the load type (Caltrans, 2011). A greater safety factor of 2.17 was applied to vehicle loads specified in the AASHTO specifications (i.e., HS20) due to the higher variability and uncertainty of live loads and a lower safety factor of 1.3 was applied to dead loads (Fu et al., 2003).

In 1994, AASHTO adopted the probability-based Load and Resistance Factor Design (LRFD) specifications. The LRFD method was an extension of the LFD design method, applying load and resistance factors determined based on statistical methods and pre-selected probability of failures, considering the known variability of applied loads and material properties. The LRFD method provides a more uniform level of safety and reliability which should lead to superior serviceability and long term maintainability. (Khan, 2010 & FHWA, 2011)

The AASHTO Load Resistance Factor Design (LRFD) specifications introduced the HL93 design vehicle in 1998 (Fu et al., 2003). This is similar to an HS20 truck with the addition of a 948 kg/linear metre lane load and reduced load factor of 1.75. Based on the AASHTO LRFD specifications, the extreme force effect is taken as the larger of: (1) the effect of the design tandem combined with the effect of the design lane load; or (2) the effect of one design truck with variable axle spacing combined with the effect of the design lane load (AASHTO, 2012).

In summary, the traditional AASHTO bridge design specifications (AASHTO, 1996) consisted of conservative safety levels in bridge design with a 0.55 factor applied to the yield stress limit (equivalent to 1.82 load factor applied to loads). With the introduction of the AASHTO load factor design, a greater safety factor of 2.17 was applied to vehicle loads specified in the AASHTO specifications (i.e., HS20) and a lower safety factor of 1.3 was applied to dead loads. This resulted in decreased capacity and cost for long span bridges and increased load effects for shorter spans. With the new AASHTO LRFD specifications of 1998, load factors were reduced to 1.75 for live load and 1.25 for dead load. However, the live load factor is applied to the HL93 design vehicle which results in a greater load effect relative to the 2.17 factor multiplied by the HS20 design vehicle (Fu et al., 2003). This is to account for future changes in truck traffic volumes and loads that may occur during the expected life of the bridge, which is accepted as 75 years in the AASHTO code.

The AASHTO design specifications are also applied in some Canadian jurisdictions. The Trans-Canada Highway has been designed for a HSS 30 design loading while all Provincial Trunk Highways (PTH) are designed for HSS 25 design loading in Manitoba. Provincial Roads (PR) can be designed for smaller loadings.

2.4.3. Bridge Rating

Increasing truck size and weight limits may result in the inadequacy of some bridges to support the heavier load. A bridge is rated to determine whether an overloaded vehicle can be allowed to cross or to evaluate the allowance of increasing load restrictions on the bridge. Selecting the allowable stress level and rating method is crucial because it determines the adequacy of bridges to support increased loads (TRB, 1990). The AASHTO Manual for Condition Evaluation of Bridges (2000) specifies two rating types: inventory and operating ratings.

Inventory or design rating indicates the permissible load under the design level of safety, which considers everyday traffic allowed to cross the bridge. In an allowable stress design procedure, an inventory stress level is the same as the design stress level, obtained by reducing the limiting stress of a bridge to 55 percent of the full stress capacity (55 percent of the yield stress). (TRB, 1990)

Using a load factor (LF) rating procedure for inventory rating, a dead load factor of 1.3 and live load factor of 2.17 are usually assigned. The resulting stresses are compared to the yield stress of steel members or the ultimate capacity of concrete members also considering appropriate strength reduction factors. The value of 2.17 is the dead load factor of 1.3 multiplied by 1.67. The load factor of 1.3 is a uniform safety factor that accounts for a 30 percent increase in all loadings, either dead or live. The 1.67 factor accounts for the variability of live load configurations other than a standard HS-load pattern. This factor also provides for potential overloads in excess of the jurisdictions legal loads. (Texas Department of Transportation, 2002)

Operating rating allows overstressing of the bridge structure due to infrequent crossing of heavy overload vehicles (relative to design loads) resulting in lower safety levels as a compromise to maximize the use of the bridge and to avoid high costs. Using an allowable stress (ASD) procedure, the operating stress level is limited to utilization of 75 percent of the full capacity of a bridge (75 percent of the yield stress). Using a load factor rating procedure, a dead load factor of 1.3 and live load factor of 1.3 are usually assigned. (Texas Department of Transportation, 2002)

The AASHTO bridge evaluation specification, Guide Manual for Condition Evaluation and Load Resistance Factor Evaluation of Highway Bridges published in 2003 uses a probabilistic approach of prescribing load factors for bridge load rating (Fu & Fu , 2006).
The AASHTO code permits the use of the operating rating method where higher stresses would be allowed on the bridge, under the condition that the bridge is well

inspected and the loads are controlled. Bridges are never intentionally loaded to the yield stress level to provide an adequate margin of safety. (TRB, 1990)

Some jurisdictions allow the bridges to be stressed on a level between inventory and operating stress levels on a regular basis. The Province of Manitoba allows 65 percent of load bearing capacity of bridges to be reached for rating old structures due to higher strength reserves from conservative designs.

2.5. INTERNATIONAL BRIDGE FORMULAE

There are six countries that have developed bridge formulae to limit the weights of heavy vehicles. These are: Australia, Canada, Mexico, New Zealand, South Africa, and the U.S. The formulae are designed specific to each country's transportation system and infrastructure characteristics and may vary significantly in terms of their general characteristics and level of restrictiveness.

2.5.1. Australia

Truck loads in Australia were originally restricted by legal limits on the axle weights and varying bridge formulae that generally limit only the maximum GVW, based on the extreme outer axle spacing. Vehicle axle spacing limits, axle weight limits, and the bridge formulae were determined by State and Territory road authorities and therefore variations existed between states. Due to the need to control internal axle weight distribution and to create uniformity amongst states, a new set of bridge formula were developed and recommended by Austroads in 1994 (Austroads, 1994) and adopted in the National Mass and Loading Regulations.

The proposed bridge formulae were developed based on the "degree of overstressing that is acceptable for Australian bridges given the expected load probabilities and the overstressing limits set by the National Association of Australian State Road Authorities (NAASRA) Bridge Engineering committee" (Austroads, 1994, p. 4)

The guiding principles for developing the new bridge formulae were to (Austroads, 1994):

- achieve optimized longitudinal load distribution;
- place minimal reliance on dimensional or other forms of regulatory controls; and
- move away from prescriptive measures and towards performance based standards to enhance productivity gains by allowing more innovation in vehicle design and operation.

The current set of bridge formula, shown in Table 1, determines the internal and external weight limits depending on the vehicle class and additional length and axle spacing restrictions.

Table 1: Australian Bridge Formulae

(1) General Access Schedule	**Bridge Formula**
• All general access vehicles or vehicle combinations with GVW up to legal limit of 42.5 tonnes	3L + 12.5
• General access vehicles and vehicle combinations and general access B-doubles with GVW from 42.5 to 50 tonnes	L + 32.5
(2) Restricted Access Schedule- B-doubles	**Bridge Formula**
• Up to GVW of 46.5 tonnes	3L + 12.5
• With GVW from 46.5 to 62.5 tonnes	1.5L + 29.5
(3) Restricted Access Schedule- Road Trains	**Bridge Formula**
• Category 1 road trains with GVW up to 132 tonnes	3L + 12.5
• Category 2 road trains with GVW up to 46.5 tonnes	3L + 12.5
• Category 2 road trains with GVW from 46.5 to 106 tonnes	1.5L + 29.5

Adapted from Austroads, 1994 and Pearson, 1998

Where L= distance in metres between the centerlines of the extreme of any group of two or more consecutive axles.

Category 1 Road Train routes are routes or areas that allow the operation of road trains up to a GVW of 132 tonnes. The bridges must be designed to a minimum specified design standard with limited span lengths of 20 metres if simply supported or 10 metres if continuous; otherwise the bridges must be deemed capable of Category 1 Road Train loading by the relevant road authority.

Category 2 Road Train routes are routes or areas that would allow the operation of road trains up to a GVW of 106 tonnes. The bridges on these routes must be designed to a minimum specified design standard but with no span length limitations. Australian A-double and A-triple truck configurations, shown in Figure 3 and Figure 4, are examples of trucks that can operate on Category 1 and 2 routes.

Figure 4: Australian A-Double Truck
Photo by A. Germanchev

Figure 3: Australian A-Triple Truck
Photo by A. Germanchev

B Double routes are routes or areas that allow the operation of B-doubles up to a GVW of 62.5 tonnes with bridges designed to a minimum specified design standard or otherwise deemed capable of supporting a B-double loading by the relevant road authority. Figure 5 shows a B-double truck configuration operating in Australia.

Figure 5: Australian B-Double Truck
Photo by A. Ritzinger

The allowable weights of the old and current (new) Australian bridge formulae are compared in Figure 6. The current set of bridge formulae allow increased gross vehicle weights relative to the old bridge formulae, however with marginal increase in bridge stresses due to better load distribution within vehicles (Austroads, 1994).

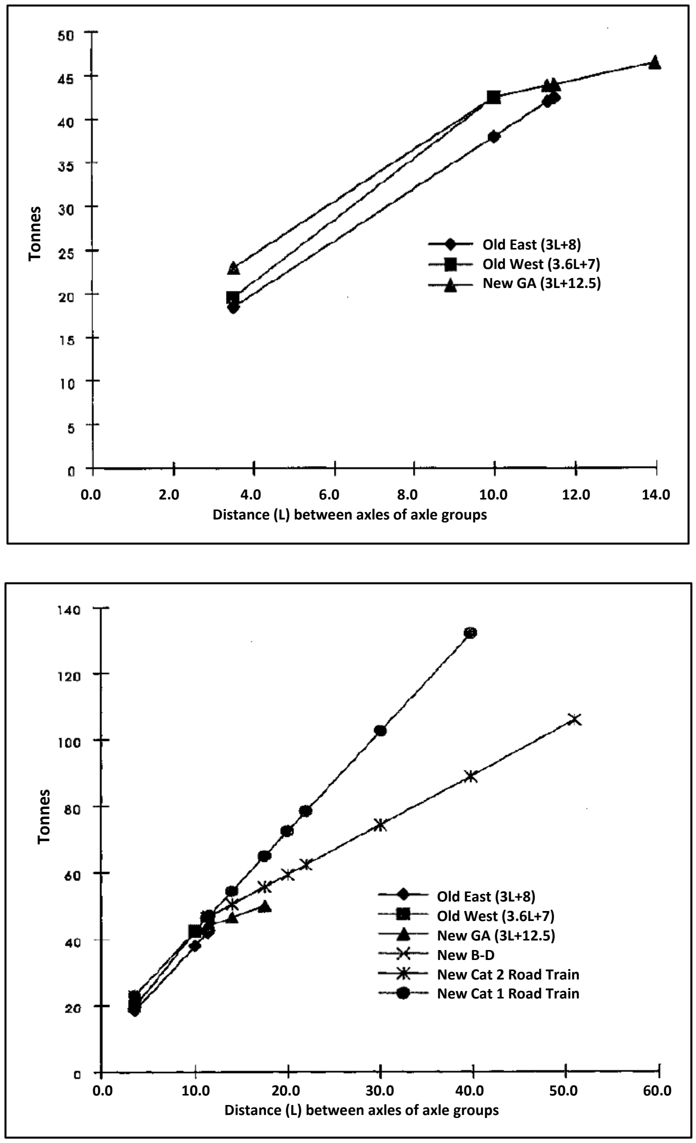


Figure 6: Comparison of Old and Current (new) Australian Bridge Formulae

GA= general access trucks, BD= B-double trucks

Source: Austroads (1994)

2.5.2. Ontario, Canada

Ontario is the only province in Canada that uses a bridge formula. The Ontario Bridge Formula (OBF) was introduced in the Highway Traffic Act in 1970, based on a 1967 survey of observed axle loads, and revised in 1978 (Argawal & Billing, 1986). This formula introduced the “Equivalent Base Length” (B_M) concept, calculated from the number of axles and axle spacing of a vehicle. B_M is an imaginary length on which the total concentrated load of any series of consecutive axles is uniformly distributed such that the moment envelope along the bridge would be similar to that caused by the concentrated loads. (O'Connor & Shaw, 2000)

The equivalent base length, B_M, is calculated by the following formula (Miao & Chan, 2002):

$$B_m = \frac{4}{W}\sum_{i-1}^{N}|P_i x_i| - \frac{2(N-1)}{bNW^2}\left\{\sum_{i-1}^{N}(P_i x_i)\right\}^2$$

Where:

W= total weight of discrete loads in kN

Pi= concentrated loads in kN

xi= distance between each concentrated load and the centre of gravity of loads in meters

N= total number of axle loads

b= distance between the centerlines of the first and last axle (i.e., vehicle wheelbase) in metres

Every combination of adjacent axles of a vehicle has a weight and an equivalent base length which can be plotted, with the upper bound of the points providing the equivalent base length signature of the vehicle.

The OBF was developed based on a truck size and weight survey conducted in 1967 which identified operating truck configurations and axle loads. The equivalent base length (Bm) signatures of the observed loads were calculated and plotted. The OBF curve lies slightly below the upper bound of the survey data. (O'Connor & Shaw, 2000)

The Ontario Bridge Formula of 1978 is (Argawal & Billing, 1986):

$$W = 10.0 + 3.0\, B_M - 0.0325 B_M^2$$

Where:

W= allowable weight in tonnes

B_M= equivalent base length in metres

2.5.3. Mexico

The Secretaria de Comunicaciones y Transportes (SCT) of Mexico uses a bridge formula for the regulation of gross vehicle weights for trucks operating on Mexican Federal roads. The structure of the Mexican bridge formula is similar to the U.S. Bridge Formula B, but with different coefficient values used for different road classifications.

The Mexican bridge formula is (NAFTA, 1997):

$$PBV = \alpha \times [\frac{L * N}{N-1} + (3.66 * N) + 11]$$

Where:

PBV= maximum gross vehicle weight in kg

L= distance between the extreme axles in metres (from first axle on vehicle to last axle on trailer or semitrailer)

N= number of axles on the vehicle combination

The values for the coefficient, α, are provided for the different road classifications in Table 2.

Table 2: Coefficient α values for the Mexico Bridge Formula

Road Classification	Coefficient α
Class A4 and A2	930.43
Class B4 and B2	899.41
Class C	854.46
Class D	845.24

Source: Adapted from NAFTA (1997)

The descriptions of the road classifications are:

- *Class A4 (four lane) and A2 (2 lane) routes:* geometric and structural characteristics of highway allow all vehicles authorized by the regulations to travel with the maximum dimensions, capacity, and weights.
- *Class B4 (four lane) and B2 (2 lane) routes (Primary Network):* geometric and structural characteristics provide interstate linkages and connections to Type A Highway network.
- *Class C routes (Secondary Network):* geometric and structural characteristics allow service at the state level, and provide connections to the Primary Network.
- *Class D routes (Feeder Network):* geometric and structural characteristics allow service at the municipal level and provide connections to Secondary Network.

2.5.4. New Zealand

The Vehicle Dimensions and Mass (VDAM) Rule 41001 specifies the allowable truck size and weight limits in New Zealand (Minister of Transport, 2002). In addition to the axle weight limits, a table is provided that specifies the maximum allowable weight for a series of axles based on the axle spread to a maximum of 44 tonnes. The table is referred to as a bridge formula, since the weights are determined based on distance between axles for the purpose of preventing overloading of bridges. The values of the 'bridge formula' table are presented in the form of a graph in Figure 7. (TERNZ Transport Research, 2010)

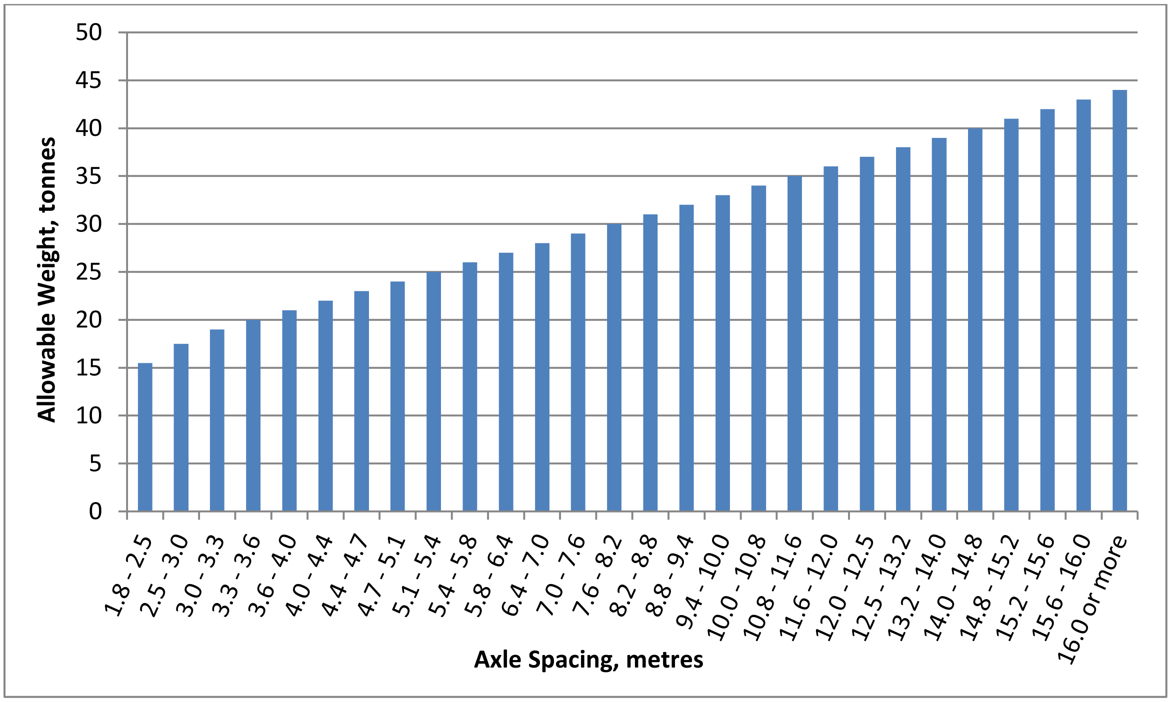


Figure 7: New Zealand's Bridge Formula Table
Source: Adapted from Land Transport Safety Authority of New Zealand (2002)
Note: The upper bound axle spacing limits are included in the following greater allowable load category (for example an axle spacing of 2.5 m would be allowed a weight of 17.5 tonnes)

2.5.5. South Africa

South Africa's bridge formula has changed over the years to become more permissive, due to the extent of overloading and demand for heavier vehicles. The maximum gross vehicle weights are limited by limiting the maximum length of vehicles. The evolution of the bridge formula over the years, as well as the length and weight limits, are shown in Table 3.

Table 3: South African Bridge Formulae

Description	Bridge Formula	Length limit (m)	GVW limit (tonnes)
Original	P = 1.8 L + 16	20	None*
As of July 1992	P = 2.1 L + 15	22	None*
As of March 1996 (current)	P = 2.1 L + 18	22	56

Source: Adapted from Nordengen, 1998
* GVW limited by length restrictions only
Where: P = maximum allowable weight in tonnes
L= distance in metres between the centres of the extreme axles of any group of axles

Prior to March 1996, the axle weight limits were 8.2, 16.4, and 21 tonnes for single axle with dual tires, tandem axle units, and tridem axles, respectively. With the relaxation of the bridge formula to 2.1 L + 18 after March 1996, the axle weight limits were increased to 9, 18, and 24 tonnes respectively, along with the introduction of a gross vehicle weight limit of 56 tonnes (Nordengen, 1998).

The bridge formula prior to 1996 (2.1 L + 15) allowed gross vehicle weights up to 59 tonnes for long combination vehicles. However, the implementation of the GVW limit of 56 tonnes accompanied with the new formula (2.1 L + 18) placed most long combination vehicles (lengths greater than 22 metres) at a disadvantage. However, six axle tractor-semitrailers (with a tridem axle group) gained the most benefit with an increase in payload of approximately three tonnes. (Nordengen, 1998)

A separate bridge formula is used for the restriction of “abnormal” vehicles with permit requirements. The formula is used for oversize/overweight vehicles up to a maximum GVW of 125 tonnes. Under a permit, articulated vehicles are limited to a length of 26 metres and combination vehicles to a length of 28 metres. (Transport Republic of South Africa, 2010)

The bridge formula for abnormal loads is (Transport Republic of South Africa, 2010):

$$M_{AL}= EW^* (6.85+ 0.00145^*AD)$$

Where:

M_{AL}= allowable mass of the group of axles in kg

EW= effective width of the vehicle in millimetres

AD= distance between the centres of the first and last axles of any group of axles in millimetres

The Effective Width (EW) is the dimension used in calculating loads on bridges, and is determined by adding 1.2 metres to the width of a vehicle measured to the outside of the tires. (Transport Republic of South Africa, 2010)

The abnormal load bridge formula table only provides allowable weights for a maximum axle spacing of six metres, which would mean the North American long combination vehicles (Turnpike Double and Rocky Mountain Double) would not be able to operate in South Africa under these criteria.

2.5.6. United States

In 1956, the U.S. federal government set the first significant national restrictions on truck weights which were provided for the planning, financing, and construction of the Interstate Highway System. The Federal-Aid Highway Legislation set the maximum gross vehicle weight (GVW) on Interstate highways at 73,280 lb with 18,000 lb on a single axle and 32,000 lb on a tandem axle (TRB, 1990).

Following the recommendations of the 1964 study by the Secretary of Commerce (U.S. Secretary of Commerce, 1964), congress modified the law in 1974 through the Federal-Aid Highway Amendments Act by: (TRB, 1990; U.S. House of Representatives, 2011)

- Increasing and limiting the gross vehicle weight to 80,000 lb.

- Increasing limits on axle loads to 20,000 lb for single and 34,000 lb for tandem axles.
- Introducing a bridge formula, referred to as Bridge Formula B, that specifies the maximum allowable weight on any group of consecutive axles based on the number of axles in the group and the distance from the first to the last axle in the considered group.

The Federal Bridge Formula B (BFB) is:

$$W = 500 * (\frac{LN}{N-1}) + 12N + 36$$

Where:

W= gross weight on any group of two or more consecutive axles to the nearest 500 lb

L= distance in feet between the extreme of any group of two or more consecutive axles

N= number of axles in the group under consideration

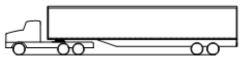
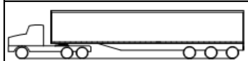
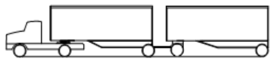
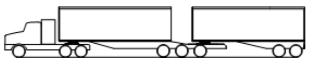
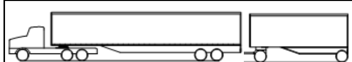
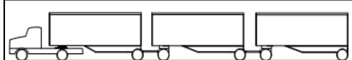
The increase in weight limits was generally due to realizing the importance of heavy vehicles to the nation's economy, an energy conservation measure, and an attempt to restore truck productivity losses associated with the 55 mph speed limit imposed on December 1973 (Noel et al., 1985).

The 80,000 lb gross vehicle weight cap means that where the BFB allows weights higher than 80,000 lb, the cap governs and the vehicle is only allowed a maximum GVW of 80,000 lb. In this research, the "uncapped BFB" refers to the BFB allowable weights with no additional weight limits and the "capped BFB" refers to the BFB allowable weights limited at the 80,000 lb gross vehicle weight limit.

While the 80,000 lb limit is intended to apply on all Interstate Highways, there are many exceptions to the rule as a result of grandfather rights implemented in the Federal Aid Highway Act of 1956 and 1975, and with the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 (Sivakumar et al., 2007). Under a “grandfather clause” in the federal statutes, those states with higher weight limits at the time of enacting this law were allowed to maintain the higher weight limits, provided they comply with Federal Bridge Formula with respect to inter-axle spacing and required number of axles to achieve that GVW. For example, the maximum GVW limit on Interstate Highways in North Dakota is 105,500 lb (NDDOT, 2010) and Michigan is 164,000 lb (MDOT, 2012).

A series of practical U.S. truck configurations is shown in Table 4, identified in the Joint Transport Research Committee study (ITF/OECD/JTRC, 2010) and the Western Uniformity Scenario Analysis study (U.S. DOT, 2004). The three configurations, Rocky Mountain Double, Turnpike Double, and Triple, are known as Long Combination Vehicles (LCVs). These LCV configurations have varying weight restrictions in different states and generally higher weight and dimensional restrictions in Canada. For instance, in the U.S. a turnpike double consists of two 48 ft trailers with GVW restrictions ranging between 48 to 67 tonnes (105,500 to 147,000 lb) amongst different states, while in Canada it consists of two 53-ft trailers at 62.5 tonnes, with British Columbia, Alberta, Saskatchewan, Ontario, Yukon, and North West Territories allowing 63.5 tonnes (Woodrooffe et al. 2010).

Table 4: U.S. Truck Configurations

Configuration	Title	Trailer Length, ft	GVW, t (lb)^
	3S2	40 45 53	33.3 (73,280) 36.4 (80,000) 36.4 (80,000)
	3S3	53	36.4 (80,000)
	STAA* Double	28.5+28.5	36.4 (80,000)
	8-axle B-train	85 (total length)	48 – 62.6 (105,500-137,800)
	Rocky Mountain Double	40+28.5 48+28.5	48 – 58.6** (105,500-129,000)
	Turnpike Double	48+48 53+53	48 – 66.8** (105,500-147,000)
	Triple	28.5+28.5+28.5	41 – 58.6** (90,000-129,000)

* STAA means Surface Transportation Assistance Act
**The maximum length of LCVs varies depending on the State, where some regulate total length, some combined length of trailers, and others length of individual trailers.
^ Maximum GVW depends on the State or road network where these vehicles are operating.
(Sources: U.S. DOT, 2004 and ITF/OECD/JTRC, 2010)

2.5.6.1. Development of U.S. Bridge Formula B

Bridge Formula B was developed based on the criteria to limit the extent to which the imposed stresses from operating vehicles are to exceed the stresses used in bridge design. The purpose of this formula is to protect bridges on the Interstate Highway System from severe overstressing by limiting truck gross and axle weights through controlling the number and spacing of truck axles (TRB, 1990).

BFB includes the number of axles as a parameter for determining axle weights. However, research has found that “the relation between the allowable weight and number of axles is sometimes contrary to the dependence of stresses on the number of axles” (Contractor, 2005, p. 1). Increasing the number of axles in an axle group without increasing the length of the vehicle has very little effect on bridge stresses and may actually result in the increase of imposed stresses due to the concentration of loads; however the higher number of axles is substantially beneficial to pavements (Battelle, 1995).

AASHTO Codes are used for the design of bridges in the U.S. The majority of bridges on the Interstate Highway System are designed for a minimum design load of HS20 (tractor-semitrailer truck at 72,000 lb), while the non-Interstate Highways are designed for a minimum design load of H15 (single unit truck at 30,000 lb). However, to account for heavier loads, some states use HS25 loads (25 percent larger than HS20 loads). BFB was developed such that the design allowable stresses on HS20 bridges are exceeded by no more than 5 percent and H15 bridges by no more than 30 percent. The 5 percent overstress criterion on HS20 bridges was based on the fact that the majority of heavy vehicles would travel on the Interstate and primary highways. Setting a more restrictive overstress criterion would reduce the fatigue damage on the bridges that occur due to repetitive loading. (TRB, 1990)

The U.S. Bridge Formula B has received several critiques since its implementation in the Federal-Aid Highway Legislation in 1974. The formula was derived based on judgment about the extent to which the increased allowable loads would reduce safety margins built into the design of existing bridges, while not considering a benefit-cost analysis of the consequences of changes in truck sizes and weights, on productivity, and bridge life and serviceability (TRB, 1990).

The current U.S. BFB has been criticized for being overly permissive for longer trucks (truck combinations with more than six axles) if the maximum 80,000 lb GVW limit is not in place. Without the GVW limit, a long nine axle combination truck could overstress HS20 bridges by as much as 12 percent under the BFB allowable weights, depending on the bridge span length (Battelle, 1995). The permitted percentage of overstress on bridges varies amongst states; therefore some bridges may not require posting for increased weight limits.

Furthermore, the 80,000 lb GVW cap was selected arbitrarily and is deemed too restrictive on longer combination vehicles. Bridges on the Interstate Highway can carry more weight than those allowed by the capped BFB without overstressing HS20 bridges beyond the permissible limit of 5 percent (Contractor, 2005). However, many bridges on non-Interstate Highways would be deficient if the maximum GVW was increased. This limitation indicates the inadequacy of the arbitrarily selected GVW cap. Ghosn (2000) determined more rational overstress criteria using a structural reliability theory approach which relates the statistics of static and dynamic bridge load effects to the resistance of bridges. This takes into account the possibility of overloads and simultaneous truck presence.

Bridge Formula B has also been criticized for applying overly conservative weight limits on shorter trucks. The bridge formula may result in lower axle weight limits than the permissible 20,000 lb on single and 34,000 lb on tandem axles as well as a lower GVW limit than the permissible 80,000 lb. Only a small percentage of bridges on the Interstate Highway (about 2 percent) are designed for H15 loads or less, therefore removing the 30 percent overstress criterion for H15 bridges could allow much higher weights on trucks with shorter wheelbases. (TRB, 1990)

The BFB was developed based on single span bridges only, while most bridges on the Interstate Highways are designed as continuous span bridges which behave and respond differently to increases in truck weights with critical loadings at intermediate supports (Battelle, 1995). The Organization for Economic Cooperation and Development and International Transport Forum (ITF/OECD/JTRC, 2010) jointly conducted an analysis of imposed load effects on a variety of bridge types and span lengths for a series of international truck configurations. They found that BFB load effects fit the mid-span moments induced on a 20 metre simply-supported bridge. This is because this length is close to the average vehicle length. Figure 8 shows the relative aggressiveness of a series of truck configurations to the European five axle reference truck for different simply supported bridge spans (with sample truck configurations indicated in the figure). The figure shows that BFB load effects follow the actual vehicle load effects on a 20 metre single span bridge; therefore, providing a good envelope for the mid-span bending moment for spans up to 20 metres, however possibly not for greater spans (Jacob et al., 2010).

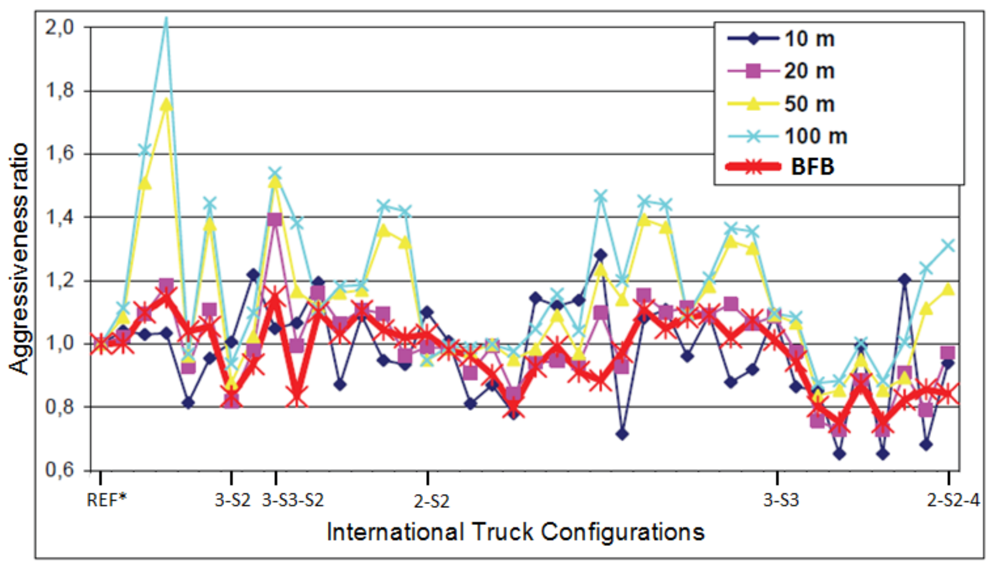


Figure 8: Relative Aggressiveness at Mid-Span (moments) for International Truck Configurations
(Source: Jacob, et al, 2010)
*Ref= European five- axle reference truck (2-S3)

2.5.6.2. Implications of the BFB on Truck Fleet, Productivity, and Safety

Truck size and weight regulations involve trade-offs between road freight productivity and the cost of highway infrastructure, and they have implications for highway safety, traffic flow, finance, and economic productivity (TRB, 1990).

A particular concern of truck size and weight limits in the U.S. is the productivity and efficiency impacts on container movements, given the role of international trade in today's economy and recent growth in containerized and intermodal transportation. Trucks carrying fully-loaded ISO containers exceed the 80,000 lb bridge formula cap as well as BFB axle weight distribution. (Rempel et al., 2012)

On roads where the 80,000 lb cap is retained, a fully-loaded container is too heavy, given that its movement would require 90,000 to 97,000 lb, depending on the tare weight of the tractor and chassis. Constraints for their movement may also occur where the 80,000 lb cap is not used (e.g., under grandfather right provisions or on some state roads) but where inner and outer BFB requirements are applied – depending on its nature of application and constraints on vehicle design issues such as lift axles. The BFB weight limit on tridem axles of 47,000 lb does not allow the transport of a fully-loaded ISO container on a standard six-axle vehicle (that is, with a rear tridem spread between first and last axles of 2.4 m to 4.6 m) which requires a tridem carrying 51,000 lb. (U.S. Department of Transportation, 2011)

The implications of this can be important in the U.S. for many reasons, including the domestic routing of international freight, the advantages of one port over another (including country to country competition and rail-related movements), stuffing/de-stuffing requirements, inconsistent treatment among states, routes, and industries, and other inefficiencies (Rempel et al., 2012).

BFB also impacts the truck fleet since it governs the design of vehicles by prescribing the number of axles, inter-axle spacing, axle weights, and overall vehicle length for a given maximum gross vehicle weight. In order to carry higher gross weights, the length of the vehicle and/or the number of axles must increase. Therefore, BFB has resulted in unintended new truck configurations to take advantage of the allowable weights and to increase payloads (Woodrooffe, 2006). Furthermore, BFB truck configurations and allowable weights also impact infrastructure and truck productivity. There is a key trade-off between the cost associated with building and maintaining roadway infrastructure and the cost associated with the transport of goods by trucks and truck productivity. The productivity gains and transport cost savings associated with change in the bridge formula and weight limit are much greater than the additional costs imposed on highways and bridges. (TRB, 1990)

Figure 9: Dump truck with draw bar
Source: Peter Townsend (www.roadtransport.com)

BFB allows the transportation of higher cubic loads which has productivity benefits. Typically, longer combination vehicles (LCVs) such as the Turnpike Double and Triples are used for lower density cube out commodities. However, trucks carrying heavier commodities that typically weigh out before cubing out cannot utilize this additional cubic capacity. This is especially the case for specialized hauling vehicles (SHVs) that have difficulty complying with the BFB weight limits due to their short wheelbases. This has resulted in vehicles with long draw bars, to allow higher payloads by increasing the length of the vehicle while maintaining the same cubic capacity to not increase the tare weight. Figure 9 shows a seven axle dump truck with a long draw bar, which is an example of a BFB vehicle. The long draw bar may cause manoeuvrability and safety issues when travelling in urban areas due to geometric constraints.

In addition, SHVs and short combination vehicles increase the number of axles to allow the transportation of higher weights, up to 80,000 lb while complying with the BFB. The high number of closely spaced axles also creates challenges with manoeuvrability of the vehicle, specifically on horizontal curves. The AASHTO legal loads do not represent these unintended SHV configurations and can overstress non-posted bridges by up to 50 percent over the current AASHTO legal loads used for posting (Sivakumar et al., 2007). Industry has resolved this difficulty by using lift axles, which allow trucks to carry higher payloads when the axle is lowered, and to improve vehicle maneuverability when the axle is lifted when the truck is empty. However, some states have banned their use due to truck maneuverability problems when lowered, stability issues when lifted, and difficulty in enforcing compliance with lift axle regulations. (Sivakumar et al., 2007)

Figure 10: Five axle flat-bed truck with a rear split tandem axle
Source: www.merritt-equip.com

Another type of vehicle modification (or axle arrangement) that has resulted from BFB is the use of split tandem axles, now a common feature of five axle tractor semitrailers carrying heavy commodities (Sivakumar et al., 2007). A split tandem axle is a widely spaced tandem axle group, up to 10 ft, allowing higher BFB weights up to 6000 lbs relative to a standard 4-ft tandem axle, to provide flexibility in load distribution (Sivakumar et al., 2007). Figure 10 shows an example of a truck with a rear split tandem axle.

With increase in GVW, the BFB increases the length of a vehicle, which has resulted in the more productive long combination vehicles. The resulting longer and heavier vehicles with higher number of axles have implications on safety and stability. A study by Woodrooffe (2006) found that Bridge Formula B had an apparent impact on the dynamic performance and brake capacity of LCVs. With the increase in vehicle mass and change in geometry and number of axles to comply with the Bridge Formula B, rearward amplification, load transfer ratio, and high speed transient off-tracking of the vehicles improved. Similarly, with increase in vehicle mass, the available brake capacity increased at a greater rate than the GVW. The increase in brake capacity is directly related to the increase in number of axles. Less influence was found on the static rollover threshold and high speed off-tracking of the vehicles. (Woodrooffe, 2006)

2.5.6.3. Other U.S. Bridge Formulae

Other U.S. bridge formulae have been developed over time to overcome some of the limitations perceived with BFB. However, none of the proposed bridge formulae have been implemented and BFB still governs. In general, a less conservative bridge formula would reduce the margin of safety; therefore increasing the likelihood of bridge damage due to overstress (U.S. DOT, 2000). This section discusses the alternative bridge formulae that have been proposed over time.

Texas Transport Institute Bridge Formula

In 1985, the Texas Transport Institute (TTI) conducted a study funded by the Federal Highway Administration (FHWA) to review the existing BFB and develop modified bridge formulae as a recommended alternative with “the intent to more fully utilize the capacity of existing bridges without significantly shortening the service life of any” (Noel, James, Furr, & Bonilla, 1985). The set of TTI bridge formulae recommended from this study were further modified to develop the TTI HS20 bridge formulae.

Unlike BFB, both of the proposed bridge formulae determine the allowable gross and axle weights based on the extreme axle spacing only and are not dependent on the number of axles. In addition, the TTI formulae do not require a gross vehicle weight limit, therefore eliminating the current arbitrary 80,000 lb GVW cap. However, the single and tandem weight limits of 20,000 lb and 34,000 lb, respectively, remain. These limits are for pavement protection and not associated with bridge load bearing capacities.

Similar to BFB, the TTI formulae are developed for simply supported span bridges, while most bridges on the Interstate Highway System are continuous spans. (Battelle, 1995)

The two proposed bridge formulae (TTI bridge formula and TTI HS20 bridge formula) are described here.

Original TTI Bridge Formula

TTI proposed a bridge formula in 1985 using the same overstress ratio criteria as Bridge Formula B (30 percent overstress limit for H15 bridges and 5 percent overstress limit for HS20 bridges) but with more effectiveness in matching the specified overstress ratios (Ghosn, 2000). The issue of possible overstressing greater than 5 percent of HS20 bridges by vehicles over 80,000 lb was also addressed.

The initial step in developing the bridge formula was to identify the lightest and therefore critical bridge which would be the bridge with the least dead load moment and shear. This is because all bridges must be able to support the loads without exceeding the H15 and HS20 overstress limits. This is done by selecting bridges with the lower bound dead load to live load ratio values. Simple span bridges were only considered in the development of the formula due to limited scope.

The loads that would cause the specific overstress levels in the lightest bridge of each span length were then determined. For instance, uniformly distributed loads of every length between 8 ft and 120 ft were placed on the lightest weight bridges of every span to determine the total load (dead load+ live load+ impact) that would cause 1.3 times the design stress in H15 bridges and 1.05 times the design stress in HS20 bridges. The results of this process consisted of determining a unique gross weight for each uniform load length (which is the vehicle wheelbase over which the load is uniformly distributed) and each bridge design. (Noel et al., 1985)

It was found that the H15 bridges with the 1.3 factor governed for the lesser loads up to a length of approximately 70 ft while the HS20 loads governed for greater load lengths. Through plotting the gross weights against the wheelbase length, the following two equations were obtained (Noel et al., 1985):

$$W = (34 + L)1000\ lb \quad \text{for L< 56 ft}$$

$$W = \left(62 + \frac{L}{2}\right)1000\ lb \quad \text{for L> 56 ft}$$

Where:

W= gross weight in pounds on any group of two or more consecutive axles

L= distance in feet between the extreme of any group of two or more consecutive axles

This bridge formula allows higher weights on shorter trucks (straight trucks and short combination trucks) relative to BFB, while reducing weights for vehicles with greater than six axles. This is a disadvantage for longer combination vehicles of greater than 80,000 lb that currently operate under the grandfather law. The trucking industry generally had a negative perception of the formulae since under the TTI formulae the allowable GVW may be reduced to below 80,000 lbs and therefore would not be able to take advantage of the grandfather exemptions (TRB, 1990). This set of formulae was found to still be adequate to protect bridges from severe overstress if the truck lengths and weight limits increase, which is not necessarily the case for the current BFB (Noel et al., 1985).

As the TTI bridge formula was deemed effective for single span bridges, James and Zhang (1991) conducted a study to determine the effectiveness of this formula on four different continuous multi-span bridges designed with Working Stress Design and Load Factor Design. This formula worked well for three of the four bridges and resulted in overstress of 4 percent in excess of the 5 percent criteria for one of the bridges. This bridge is a lighter bridge designed to the Load Factor Design method, which is less conservative in design relative to the Working Stress Design bridges.

However, since the proposed formula resulted in an increase in the average equivalent axle load per truck, fatigue damage to the pavement is of concern. Therefore, although the formula is expected to protect bridge structures, the effect on pavement needed to be further evaluated. (Noel et al., 1985)

TTI HS20 Bridge Formula

TTI continued its study to modify the proposed TTI bridge formula to allow even higher weights on shorter wheelbase vehicles relative to the original TTI bridge formula, due to the trucking industry's complaints that the formula was still overly conservative for short wheelbase vehicles. (Noel, James, Furr, & Bonilla, 1985)

TTI developed the following three equations also known as the TTI HS20 formula:

$W = 1000\ (\ L + 34)$ for L< 8 ft

$W = 1000\ (2L + 26)$ for 8 ft< L< 24 ft

$W = 1000\ (\frac{L}{2} + 62)$ for L>24 ft

Where:

W= gross weight in pounds on any group of two or more consecutive axles

L= distance in feet between the extreme of any group of two or more consecutive axles

These equations are designed to protect bridges in the absence or increase of the 80,000 lb GVW limit (James et al., 1986). They remove the maximum 30 percent overstress criteria for H15 bridges and only consider the 5 percent overstress limit for HS20 bridges. This allows higher loads on shorter trucks relative to Bridge Formula B and the original TTI formula. This more liberal bridge formula may be used for networks that do not have H15 bridges, since it could result in significant overstressing in H15 bridges. However, similar to the previous TTI bridge formula, the load limits for vehicles of greater than 80,000 lb are more restrictive. Figure 11 shows the allowable weights by BFB and TTI HS20 bridge formulae for a series of North American and European vehicles. The European trucks include eight vehicles from the European Directive (1996) and six longer and heavier European Modular System vehicles provided by LCPC. The North American vehicles include two short single unit trucks, three practical semitrailer trucks, and three long combination vehicles (LCVs) which are the rocky mountain double, the triple and the turnpike double, obtained from Contractor (2005).

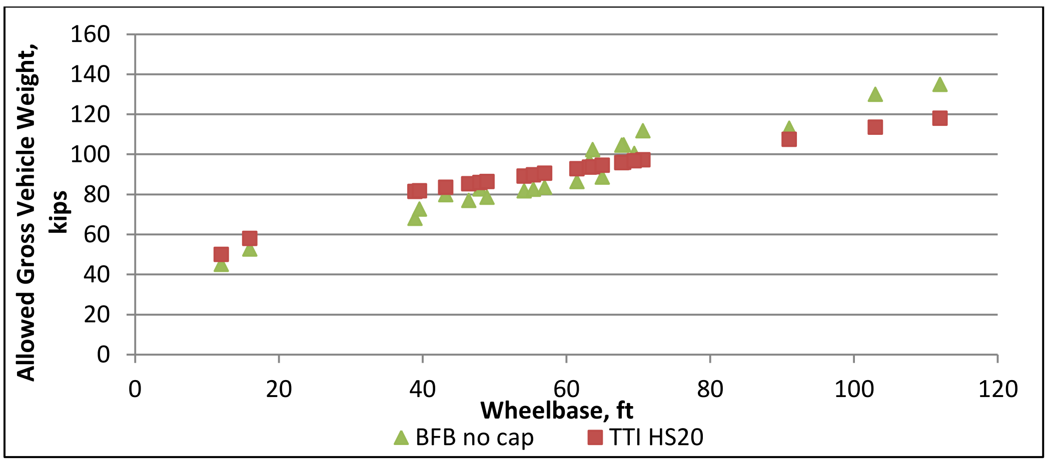


Figure 11: BFB and TTI HS20 Gross Vehicle Weights
Source: created by author using a series of European and North American Trucks (European Directive, 1996; Contractor, 2005)

Contractor (2005) compared the allowable weights from the TTI HS20 formula to the critical weights of different vehicles on different steel continuous span bridge types. This formula was found to be effective for most cases with the highest imposed overstress of 7.6 percent which was from a Rocky Mountain Double truck. Contractor recommended this bridge formula, as this formula was evaluated for steel continuous span bridges which are the most critical case for this formula. These bridges account for 7 percent of the U.S. bridges according to the FHWA Bridge Inventory Data (Contractor, 2005).

Summary of TTI formulae

The TTI bridge formulae have been developed to overcome some of the limitations associated with BFB. Although the TTI HS20 formulae were recommended by TRB (1990) and Contractor (2005), neither TTI bridge formula has been implemented. Although the formulae allow slightly higher weights on shorter combination vehicles, they are less permissive for vehicles with more than six axles, which would be a disadvantage for current trucks over 80,000 lb operating in western states under grandfather exemptions.

Transportation Research Board Developed Bridge Formula

Transportation Research Board (TRB) Special Report 225 (1990) developed a bridge formula to overcome the limitations of BFB and TTI bridge formulae - that BFB is overly restrictive for short wheelbase vehicles and the TTI formulae are too restrictive for long wheelbase vehicles. The option that was analyzed was a combined TTI HS20 and Bridge Formula B equation. In this case, the TTI HS20 formula was to be applied to single unit trucks and shorter combination vehicles with axle groups of two to six axles while BFB would be applied to long combination vehicles with seven to nine axles, namely Rocky Mountain Doubles, Turnpike Doubles, and Triples, without the 80,000 lb GVW limit. This would allow the higher weight limits for shorter trucks provided by the TTI HS20 formula, while allowing longer combination trucks to continue operating under loads greater than 80,000 lb under grandfather rights.

The proposed bridge formula is (TRB, 1990):

$W = 1000 * (2L + 26)$ for $L \leq 24$ ft

$W = 1000 * (L/2 + 62)$ for $24 < L \leq 40$ ft

$W = 1000 * (9L/16 + 72)$ for $L > 40$ ft

Where:

W= gross weight in pounds on any group of two or more consecutive axles

L= distance in feet between the extreme of any group of two or more consecutive axles

Contractor (2005) found that this formula is ineffective for the LCVs when BFB is used with no 80,000-lb GVW limit, resulting in overstress higher than the five percent overstress criteria on a few of the evaluated HS20 continuous span bridges. The Rocky Mountain Double, Triple and Turnpike Double were ineffective for one, two, and three HS20 continuous span bridges respectively, with bridge spans ranging between 50 and 280 ft.

A modification to the combined TTI HS20/BFB option was proposed to reduce the axle weights for vehicles over 80,000 lb to 15,000 lb on single axle, 34,000 lb for tractor-drive tandem axle, and 30,000 lb for other tandem axles. For vehicles less than 80,000 lb, the weight limits of 20,000 lb for single axles and 34,000 lb for tandem axles remain.

This was found to result in the same bridge effects as the original combined TTI HS20/ BFB bridge formula but with lower damage to the pavement. However trucks operating under grandfather provisions would be at a disadvantage since they are designed to take advantage of the current federal axle weight limits. (TRB, 1990)

Ghosn and Moses Bridge Formula

Ghosn and Moses developed a new bridge formula using structural reliability theory to determine the overload capacity of bridges (Ghosn, 2000). The structural reliability method uses statistical data to account for the uncertainties in evaluating the load bearing capacity of structural members and expected loads to be applied on the structure by estimating the probability of failure of structural members, and calibrating safety factors for structural design codes. (Ghosn, 2000)

This involves estimating overstress ratios based on analyzing statistics on safety margins of typical bridges including the likelihood of overloads, simultaneous truck presence, impact allowance, girder distribution, and component deterioration to produce the live load envelope that will produce the target safety index for each span length.

The formula developed by Ghosn and Moses (2000) is:

$W = (1.64\,L + 30) * 1000 \qquad \text{for } L < 50 \text{ ft}$

$W = (0.80\,L + 72) * 1000 \qquad \text{for } L > 50 \text{ ft}$

Where:

W= gross weight in pounds on any group of two or more consecutive axles

L= distance in feet between the extreme of any group of two or more consecutive axles

This formula was developed such that bridges designed to standard AASHTO Working Stress Design criteria for HS20 loading will meet a target reliability index (i.e., safety index) of 2.5 when subjected to legal truck loads over the next 50 years. The projection of truck traffic accounts for the same number of illegal and overloaded vehicles as a percentage of total traffic and for future increases in truck traffic and number of multiple truck occurrences. The proposed truck weight formula was derived to satisfy the required live load moment envelope determined from the reliability analysis. (Battelle, 1995)

Ghosn and Moses (2000) state that the development of a bridge formula must include simply supported and continuous spans for both steel and concrete bridges. This formula however is developed for simply supported steel bridges.

The proposed formula allows significantly higher weights on longer combination vehicles relative to Bridge Formula B. For example, a nine axle double trailer truck with a wheelbase of 65-ft is allowed to carry up to 108,000 lb under BFB while this vehicle could carry up to 124,000 lb under the Ghosn and Moses proposed formula (Battelle, 1995). Contractor (2005) found that this formula is effective only for the shorter trucks (for instance for the three and four axle truck selected for the study) and not for the longer vehicles as the formula weights exceed the critical truck weights for most of the bridge types.

Kurt Bridge Formula

Kurt (2000) conducted a study to modify the current U.S. bridge formula by analyzing 201 different truck configurations on 1,178 existing bridges (all bridges of a given state highway system). With the development of Bridge Formula B, the length and number of axles of trucks have increased in order to allow higher loads on vehicles. It was found that the level of overload (percent overstress) and number of overloaded bridges would increase as the truck length and number of axles increased. Kurt (2000) developed a new bridge formula to reduce the allowable loads of long trucks with large number of axles by selecting the allowable level of overloading on bridges.

The various truck configurations and bridge types were evaluated using the current bridge formula to determine the percentage of overload (relative to the operating rating) and the number of overloaded bridges in the system. The level of overloading of bridges was calculated as a percentage of allowable BFB truck weights over the allowable truck weights based on operating stress level of bridges.

The developed equation is as follows (Kurt, 2000):

$$W = 1000\,[\frac{0.5LN}{N-1} + 3N + C4]$$

Where:

W= gross weight in pounds on any group of two or more consecutive axles

L= distance in feet between the extreme of any group of two or more consecutive axles

N= number of axles in the group under consideration

C4= overloading constant

With this equation, the user can select the level of overloading in terms of the average percentage of overloaded bridges, by selecting the appropriate C4 value, determined based on the data analysis conducted by Kurt (2000). For instance, if an agency decides to allow 5 percent of its bridges to be overloaded, a value of 33 would be selected.

It was found that this equation reduces the allowable loads on longer trucks with more axles, and increases the allowable GVW on shorter trucks. Also, the maximum level of overload is reduced. For example, the Kurt bridge formula, with a C4 value of 33, results in reduction of the maximum level of overloading amongst all truck-bridge combinations from 100 percent (double the operating capacity of the bridge due to the BFB allowable loads for the very long trucks with large number of axles) to 64 percent.

Contractor (2005) compared the allowable GVWs from this formula to the critical weights from ten representative U.S. trucks on different HS20 and HS20 modified (HS20 design truck modified by factor of 1.25) continuous span bridges and found that the Kurt (2000) bridge formula is very effective in restricting stresses within permissible limits. The reason for the lack of attention to this formula was thought to be due to: (1) the dependence of the formula on the number of axles similar to BFB which can sometimes be contrary to the dependence of stresses on number of axles, (2) being more restrictive relative to the TTI HS20 formula for short and medium length trucks, (3) being more complicated than the TTI HS20 formula due to the C4 coefficient (Contractor, 2005). The

C4 coefficient however can be fixed to a constant value to remove some of the complexity of the formula.

2.5.6.4. Comparison of U.S. Bridge Formulae

Contractor (2005) evaluated the adequacy of the TTI HS20 formula by comparing the allowable weights calculated from this formula to the critical gross weights causing 5 and 10 percent overstress in HS20 and HS20 modified bridges (HS20 design truck modified by factor of 1.25). The critical weights are obtained by loading sample representative bridges under 10 different practical trucks. The 10 trucks used in the analysis consist of short, medium, and long combination vehicles.

Mostly longer span continuous steel bridges designed by load factor design (LFD) were analyzed. This is because continuous long span bridges are critical in determining loading limits, since they undergo larger negative bending moments that must be taken into account. Also, load factor design is less conservative than working stress design and therefore, bridges designed to LFD are typically more critical. Steel bridges have a smaller dead load effect and are therefore the most critical bridge type.

Nine of the lightest continuous bridges were selected by Contractor (2005) as test bridges along with a set of ten vehicle configurations including both design vehicles and actual operating vehicles of short and long combinations. The dead load moments and maximum live load moment envelopes were calculated using a TTI-developed software, known as BMCOL51. The critical GVWs of the various vehicle configurations were calculated for the various selected bridges and compared to the allowable GVWs from the BFB and TTI bridge formula.

Figure 12, developed by Contractor (2005), shows the critical weights using 5 percent overstress criteria relative to the TTI HS20 formula allowable weights. Contractor found that the TTI HS20 formula is effective for most cases in restricting the overstress to within a 5 percent limit, and effective in all cases with a 10 percent overstress criteria. With the 5 percent overstress criteria, the TTI HS20 formula is not effective in five cases, shown in Figure 12. Two of the cases involve a 40-ft and 45-ft 3S2 vehicle on a two-span continuous bridge (Bridge 2) while the other three cases involve LCVs on another two-span continuous bridge (Bridge 3), where both bridges are theoretical bridges and may not be as conservatively designed as actual bridges.

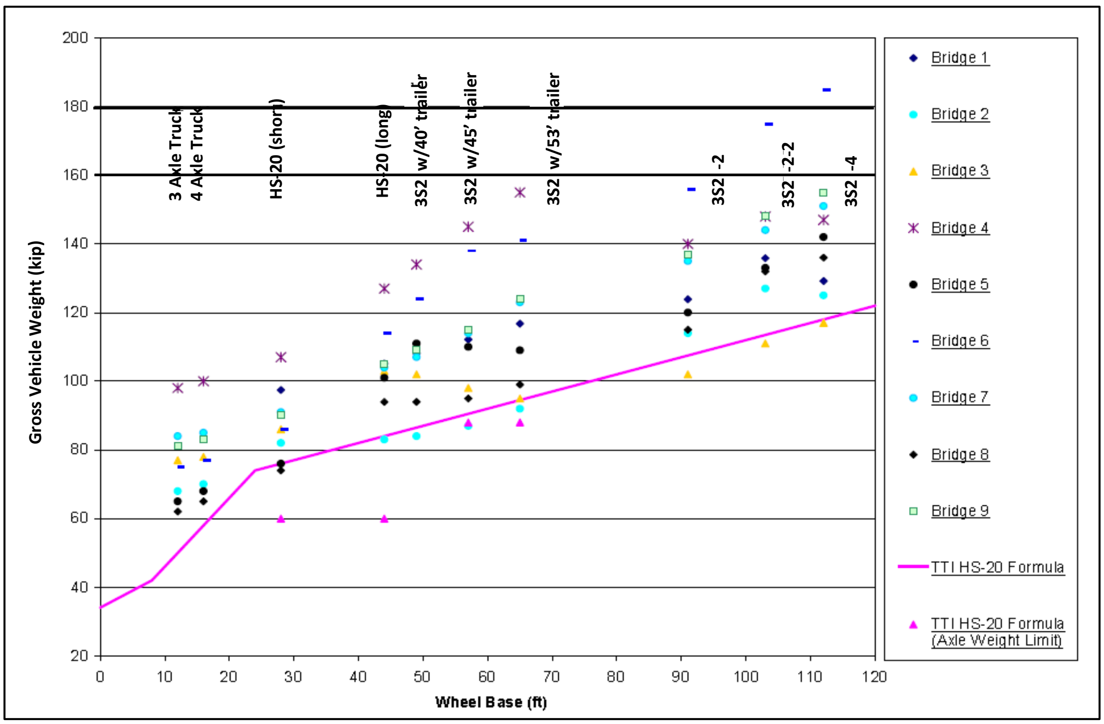


Figure 12: TTI HS20 and Critical Weights for Selected Vehicles Considering 5% Overstress
(Source: Contractor, 2005)

In addition to the TTI HS20 formula, Contractor (2005) compared several other proposed U.S. bridge formulae to determine their effectiveness. Figure 13, developed by Contractor (2005), shows the calculated GVWs from the different formulae by various wheelbase lengths. It is found that the Ghosn (2000) formula is the most permissive, followed by TRB 1990, TTI HS20/Formula B, Kurt 2000, TTI-HS20, and Bridge Formula B. BFB is the most conservative of the formulae due to the 80,000 lb GVW limit.

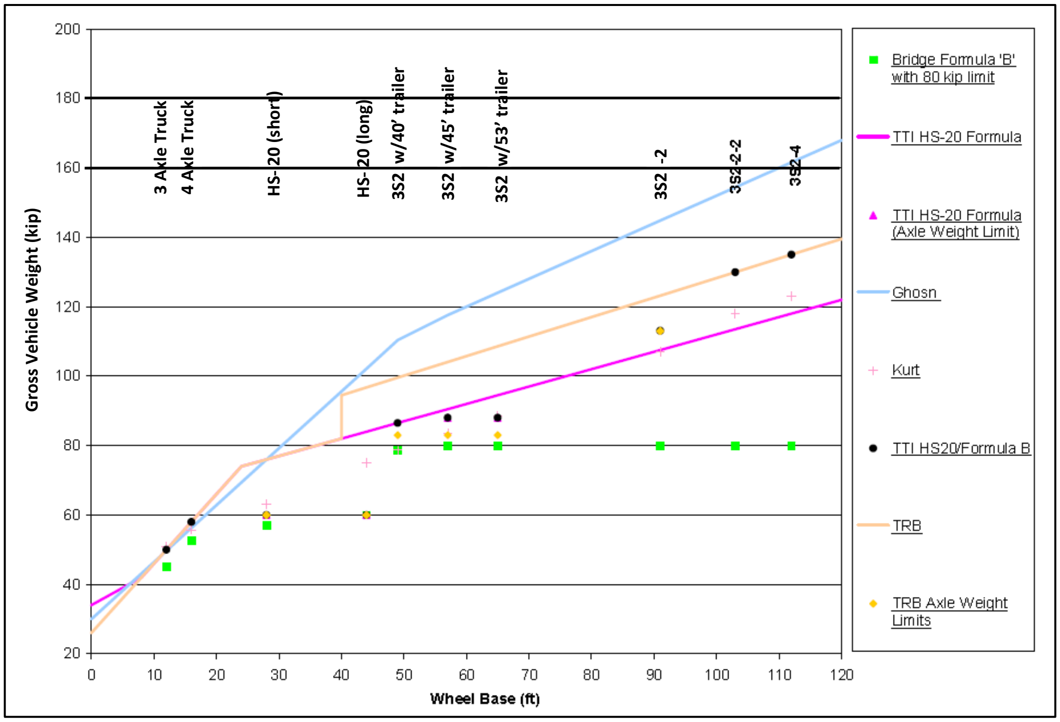


Figure 13: GVWs of Selected Vehicles from the Current and Proposed U.S. Bridge Formulae
(Source: Contractor, 2005)

It is found that the Bridge Formula B is generally over conservative relative to the other bridge formulae as well as the critical loads on a bridge. It is good for medium length trucks but too limited for shorter trucks. In addition, "the 80,000 lb arbitrary limit restricts longer trucks from carrying higher loads that can be carried without overstressing the bridge over the permissible limit. This is making BFB uneconomical and calling for the development of a new formula." (Contractor, p 135, 2005)

Contractor (2005) found the TTI HS20 formula is effective in most cases, which means the allowable weights did not exceed the critical loads on a bridge. The highest caused overstress in the evaluated bridges was 7.6 percent which was for the case of a Rocky Mountain Double, with the design overstress criteria of 5 percent.

Contractor (2005) recommends the replacement of the current bridge formula with the TTI HS20 formula to allow the more economic operation of longer combination vehicles over the 80,000 lb weight limit while not causing very high overstress of bridges.

Ghosn and Moses (2000) developed a bridge formula using the structural reliability theory and estimated the number of bridges that would be deemed deficient under the implementation of this formula. From the number of estimated deficient bridges it was estimated that an additional $34 billion of bridge replacement or upgrading would be required (U.S. DOT, 2000).

TRB Special Report 225 (1990) estimated the additional bridge costs required using an operating rating level to upgrade design loads, replace existing bridges, and fatigue damage costs associated with different truck size and weight scenarios. The scenarios included the combined TTI HS20/Formula B, uncapped TTI HS20 bridge formula, capped TTI HS20 bridge formula, using Canadian interprovincial limits, the National Truck Weight Advisory Council (NTWAC) scenario which proposed to allow significantly higher weights on specialized hauling vehicles with short wheelbases, and uncapped Bridge Formula B.

The results show the highest bridge cost ($3,040 million per year) is associated with the replacement of bridges on Interstate Highway System, primary, and non-primary highways under the NTWAC Scenario. Next to the NTWAC scenario, implementing the Canadian limits have the highest overall additional costs ($2,410 million per year). Implementing the TTI HS20 bridge formula would have the lowest infrastructure cost of all the scenarios ($350 million per year) followed closely by the uncapped scenario ($440 million per year). (Battelle, 1995)

In addition to bridge costs, TRB (1990) also determined costs associated with transport savings and pavements for the various scenarios. It was found that all scenarios resulted in an overall net cost savings due to the transport cost savings exceeding the increase in infrastructure costs. The Canadian Interprovincial Limits resulted in the highest net cost savings by far, followed by the uncapped TTI HS20 bridge formula, and the combined TTI HS20/ BFB scenario.

TRB Special Report 225 (1990) recommends the replacement of the current BFB with the TTI HS20 formula. Truck costs would decrease by $2.4 billion per year if all states adopted this formula.

TRB (1990) also estimated the impact of the specified scenarios on total vehicle miles of travel (VMT) by heavy trucks, fatal accidents and diversion from rail. Both VMT and fatal accidents would decrease for all the specified scenarios permitting higher weight limits. Rail ton-miles would also decrease for all the scenarios with the implementation of the Canadian Interprovincial limits resulting in the highest rail diversion of 7 percent of the current rail traffic. The three other scenarios involving the elimination of the GVW limit (uncapped BFB, combined TTI HS20/ BFB, and uncapped TTI HS20) also resulted in significant rail divergence of 2 to 3 percent.

2.6. SUMMARY REGARDING BRIDGE FORMULAE

Bridge formulae are a method of regulating truck size and weight while ensuring the protection of infrastructure. The level of efficiency of the formula varies depending on the design criteria used in the development of the formula, and the compatibility to the jurisdiction’s infrastructure and truck fleet characteristics. Issues associated with the effects of the bridge formulae are evident through the experience of jurisdictions using bridge formulae as a method of truck size and weight regulation.

Six countries [U.S., Canada (only in Ontario), Mexico, Australia, New Zealand, and South Africa] use bridge formulae to limit the weights of heavy vehicles. The formulae are designed specific to each country's transportation system and infrastructure characteristics and may vary significantly in terms of their general characteristics such as the format, parameters, constraints (e.g., truck length, gross vehicle weight), and application method (e.g., route class specific, axle combinations).

Table 5 summarizes the key characteristics of the different existing bridge formulae. Identifying and comparing the characteristics of different bridge formulae helps establish common themes used in their development and important characteristics to consider in the development of new bridge formulae.

Table 5: Characteristics of International Bridge Formulae

Bridge Formulae	Characteristics
U.S. Bridge Formula B	• Depends on axle spacing and number of axles • Applied to every axle combination • GVW limit of 36.4 tonnes (80 kips) by Federal law
Mexico	• Similar format to U.S. BFB • Allowable weight varies depending on the route classification (Class A, B-primary, C-secondary, or D-feeder) • Applied only to the extreme outer axles to determine allowable gross vehicle weight
Canada	• Developed and used by Ontario only • Depends on Equivalent Base Length (EBL) • Applied to all axle combinations • GVW limit of 63.5 tonnes
South Africa	Two different bridge formulae- applied to every axle combination: • Legal loads (up to 56 tonnes and length limit of 22 meters): depends on axle spacing only • Abnormal loads: depends on axle spacing and Effective Width (EW) of the vehicle
Australia	• Depends on route and vehicle classification • Applied to all axle combinations • GVW limit of 42.5 tonnes for general access vehicles
New Zealand	• Bridge formula table • Limited to 44 tonnes

Source: Developed by author based on various publications from each country

Based on the critiques of BFB, experience from other countries implementing bridge formulae, and the characteristics of existing bridge formulae, principal highlights and issues to consider in the development and implementation of new bridge formulae are the following:

- The 80,000 lb GVW cap in the U.S. was selected arbitrarily and is deemed restrictive for the truck fleet and infrastructure. The overstress criteria used in the development of BFB have also been selected arbitrarily and have failed to consider impacts of fatigue damage or the possibility of overloads and simultaneous truck presence. Ghosn (2000) determined more rational overstress criteria using a structural reliability theory approach which relates the statistics of static and dynamic bridge load effects to the resistance of bridges.

- Due to the large range of truck configurations within a jurisdiction, it is difficult to develop one bridge formula suitable to adequately regulate weights on all truck configurations. This is evident in the inadequacy of the BFB to fairly limit weights on Specialized Hauling Vehicles and Long Combination Vehicles. South Africa has developed two bridge formulae to separately regulate legal loads for the standard general access vehicles and oversize/overweight vehicles. The alternative U.S. bridge formulae that have been developed and proposed over the years, including Ghosn (Ghosn, 2000) and James (James et al., 1986) comprise a set of bridge formulae that regulate heavy vehicle weights for ranges of truck lengths.

- In addition to the wide range of truck configurations, the strength capacity of bridges varies significantly. In the case of the BFB, considering both H15 and HS20 bridges in a bridge formula was deemed too restrictive for HS20 bridges (James et al., 1986). The proposed U.S. TTI HS20 bridge formulae removed the overstress criteria of H15 bridges, and only considered bridges designed to HS20 design loads in the development of the formula. This allows acceptable higher weights on HS20 bridges, however may result in unacceptable overstressing of H15 bridges. The Mexico and Australian bridge formulae follow the same approach where different weights are allowed for different route classifications with suitable strength capacities.

- Applying a bridge formula to only the outer axles may allow axle loads on bridges that exceed the overstress criteria that were used in the development of the bridge formula. The majority of the older Australian bridge formulae were applied to the outer axles only. The current Australian bridge formulae were designed to resolve this problem by being applied to all axle combinations.

- Most States allow higher operating truck weights on their State highways, which encourages truckers to use State highways relative to the Interstate highway network. State highways may have bridges with lower strength capacities, higher congestion, and may not be geometrically suitable for large articulated vehicles.

- The bridge formula may result in unintended new truck configurations in order to take advantage of the allowable weights to increase payloads, which may result in undesirable infrastructure impacts or dynamic performances. With the implementation of any size and weight regulation there is a need to monitor the fleet as it evolves to ensure undesirable vehicles and effects are prevented. The BFB resulted in the introduction of vehicles with long draw bars, lift axles, and split tandems (Sivakumar et al., 2007). The Ontario bridge formula resulted in growth in use of widely spaced liftable axles which had poor dynamic performance and produced excessive loads on bridges and roads when raised and were highly damaging to infrastructure (Woodrooffe et al., 2010).

- Bridge formulae should be implemented such that they are complying with the design criteria. In the case of the BFB, the exemptions of specified truck configurations from compliance to the bridge formula are not adopted by some states.

- Bridge formulae should be easily understood and applied by carriers and truck enforcement staff to regulate truck weights at truck inspection stations. The OBF was deemed difficult, time consuming, and too complex to be applied, therefore tables were provided with gross weights for ranges of axle spacing of the most common configurations (Woodrooffe et al., 2010)

With the continuously changing infrastructure and truck transportation characteristics, bridge formulae must be re-evaluated and updated to ensure their adequacy to limit weights. Appropriately analyzing the impact of bridge formula truck configurations and the strength capacity of bridges allows creating a balance between impact on infrastructure and truck productivity. Weigh-in-Motion data may be used for analyzing the truck fleet characteristics for the calibration of existing bridge formulae or the development of a new bridge formula, as used for the development of a proposed Hong Kong bridge formula (Miao & Chan, 2002).

3. TRUCK SIZE AND WEIGHT REGULATIONS IN EUROPE

This chapter describes the truck size and weight regulations in Europe to understand the need and criteria for the development of a European Bridge Formula.

3.1. EUROPEAN DIRECTIVE

The European Directive 96/53/EC has been regulating truck sizes and weights in European Member States since 1996. The Directive specifies maximum allowable and permitted vehicle weights and dimensions for national and international road transport across European Member States. Although European Member States are mandated to comply with the European Directive specifications, they are permitted to allow higher vehicle weights for national travel, referred to as the Longer and Heavier Vehicles (LHVs).

The general allowable vehicle dimensions, axle weights, and gross vehicle weights are shown in Table 6. Additional weight and dimensional requirements are also specified in the Directive. The truck configurations that fall under this Directive are shown in Table 7.

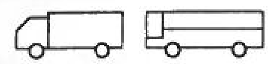
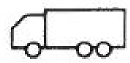
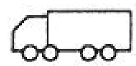
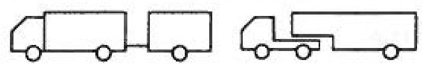
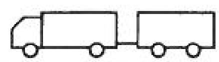
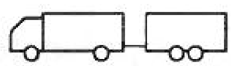
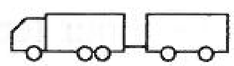
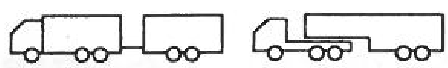
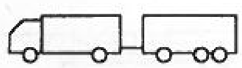
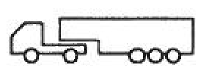
In general, the current regulation allows maximum truck lengths of 16.5 meters (for one articulation point) and 18.75 meters (for road trains with one or two articulation points), and a maximum vehicle weight of 40 tonnes for cross border travel amongst EU countries and 44 tonnes for intermodal travel of 40-ft international shipping containers.

Table 6: European Directive 96/53/EC truck size and weight limits

Vehicle Dimensions (metres)		
Maximum Height	4.00	
Maximum Width		
All trucks	2.55	
Superstructures of conditioned vehicles	2.60	
Maximum Length		
Single unit truck or tractor	12.00	
Trailer	12.00	
Truck with semi-trailer (1 point of articulation)	16.50	
Road train (1 or 2 points of articulation)	18.75	
Axle Weights (tonnes) (*d is the distance between consecutive axles)*		
Single axles	10	
Drive axles	11.5	
Tandem axles of trailers and semi-trailers	11	if d<1.0 m
	16	if 1.0 m ≤d<1.3 m
	18	if 1.3 m ≤d<1.8 m
	20	if d≥1.8
Tandem axles of tractors	11.5	if d<1.0 m
	16	if 1.0 m ≤d<1.3 m
	18	if 1.3 m ≤d<1.8 m
	19*	if 1.3 m ≤d<1.8 m
Tri-axles	21	if d≤ 1.3 m
	24	if 1.3 m <d≤1.4 m
Gross Vehicle Weight (tonnes) (*d is the distance between consecutive axles)*		
2 axles		
Single unit truck or tractor	18	
Trailer	18	
3 axles		
Single unit truck or tractor	25, 26*	
Trailer	24	
4 axles		
Tractor with two steering axles	32 *	
Truck with trailer	36	
Truck with semi-trailer	36, if the distance between the axles of the semi-trailer is between 1.3 and 1.8 meters 36, if the distance between the axles of the semi-trailer is greater than1.8 meters 38*, and if the maximum authorized weight of motor vehicle (18 tonnes) and semitrailer's tandem axle (20 tonnes) are respected	
5 axles		
Truck with trailer	40	
Truck with semi-trailer	40 44, for three axle motor vehicle with two or three axle semi-trailer carrying a 40-foot ISO container for intermodal transport.	

* Where the driving axle is fitted with twin tyres and air suspension or suspension recognized as being equivalent within the Community, or where each driving axle is fitted with twin tyres and the maximum weight of each axle does not exceed 9.5 tonnes

Table 7: European truck configurations complying with the European Directive

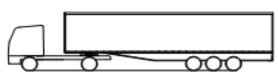
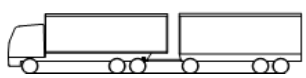
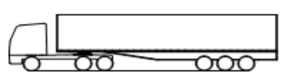
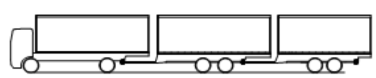
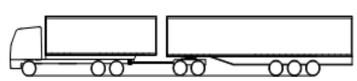
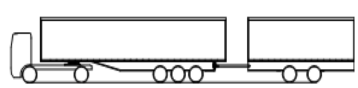
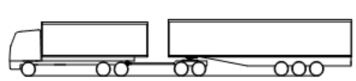
Truck Type	Truck Configurations	GVW (t)	Range of Total Length (m)
1. Two axle single unit truck		18	3.6 - 7.2
2. Three axle single unit truck		25	4.2 - 9.6
3. Four axle single unit truck		32	3.2 - 10.8
4. Two axle truck and one axle trailer or three axle tractor-semitrailer		23	6.8 – 13.1
5. Two axle truck and two axle trailer		36	10.8 – 18.6
6. Two axle truck and tandem axle trailer		26	8.7 – 15.1
7. Three axle truck and two axle trailer		40	11.4 – 18.75
8. Three axle truck and tandem axle trailer or five axle tractor- semitrailer		40	8.4 – 18.75
9. Two axle truck and three axle trailer		40	11.4 – 18.75
10. Four axle tractor-semitrailer		40	7.4 – 15.5
11. Five axle tractor-semitrailer		40	8 – 17.9
12. Six axle tractor-semitrailer		40	7.8 – 18.75

Note: Truck configurations are not to scale.
Source: provided by IFSTTAR, 2010

3.2. OTHER TRUCK SIZE AND WEIGHT REGULATIONS

European countries are allowed to set the maximum vehicular weight limits at higher levels than the European Directive for travel within their own country. Many countries have set their maximum load limits to 44 tonnes, 48 tonnes (Denmark and Czech Republic), and 50 tonnes (Netherlands) instead of 40 tonnes, while some Nordic region countries have been using the modular concept (International Transport Forum, 2011). The European Modular System (EMS) vehicles are up to 25.25 meters in length and 60 tonnes in gross vehicle weight. Finland and Sweden have been operating these vehicles since 1997. The European longer and heavier vehicles configurations are shown in Table 8.

Table 8: European Longer and Heavier Vehicles (including EMS vehicles)

Truck Type	Truck Configurations	GVW (t)	Total Length (m)
13. Five axle tractor-semitrailer		44	18.75
14. Three axle truck and three axle trailer		48	18.75
15. Six axle tractor-semitrailer		48	18.75
16. EMS- six axle triple trailer combination		50	25.25
17. EMS- three axle truck and five axle trailer		60	25.25
18. EMS- five axle tractor-semitrailer and tandem axle trailer		60	25.25
19. EMS- three axle truck and five axle trailer		60	25.25

Note: Truck configurations are not to scale.
Source: provided by IFSTTAR, 2010

Some routes in the Netherlands are now allowed to operate these vehicles, while other countries are conducting pilot tests on designated routes; however currently no additional countries have adopted these vehicles. (International Transport Forum, 2011)

Two EMS vehicles can carry a load equivalent to the load carried by three European Directive standard trucks. The Swedish Transport Research Institute estimates that the EMS trucks can carry out as much as a third of today's truck transport in the EU (Ramberg, 2004). Principal advantages of the EMS vehicles are:

- Transporting more tonne-km (1 percent greater) with fewer vehicle-km (12.9 percent less) (Transport and Mobility Leuven, 2008).
- Reduction in fuel consumption by an average of 14.3 percent which results in a corresponding reduction in carbon dioxide emissions. This calculation is based on the presumption that both the length and weight capacity of the EMS vehicles are used to the fullest, whereas typically these vehicles cube-out rather than weigh-out. Therefore, the fuel consumption and carbon dioxide emissions are reduced even further than the quoted figure for cube-out transport. (Ramberg, 2004)
- Reducing the number of trucks on the road, thus reducing congestion if adopted on a EU-wide scale. The Swedish Transport Research Institute estimated a 40 to 60 percent increase in capacity per truck relative to the EU Directive trucks of 18.75 metre and 16.5 metres in length respectively, and a reduction in the number of international truck transport trips between 28 and 35 percent, depending on the travelled route (Backman & Nordstrom, 2002).

- Improving cost efficiency. Although higher investments in roadway infrastructure will be needed, these costs are lower than the savings in the transport sector. (Transport and Mobility Leuven, 2008)

- Reducing road wear relative to operating the EU Directive vehicles for the same cargo due to the elimination of a tractor. A study by the Swedish Transport Research Institute estimated a road wear reduction of 25 percent for the truck and semitrailer combination and 15 percent for the semitrailer and center axle trailer combination, shown in Table 8 as truck configurations 17 and 18 respectively. (Backman & Nordstrom, 2002)

A study evaluating the impact of the European Directive regulations found that 44 tonnes on six axles or 50 tonnes on seven or more axles does not create much extra damage relative to the standard 40 tonnes on five axle vehicles (Truck 11 configuration) (Transport and Mobility Leuven, 2008). However, 44 tonnes on five axles has severe impacts on infrastructure, and is recommended to not be allowed, although a number of countries currently allow these vehicles.

3.3. PROPOSED CHANGES TO THE EUROPEAN DIRECTIVE

The European Commission's department of Directorate General for Mobility and Transport (DG-MOVE) is conducting an ongoing investigation on the impact of implementing proposed revisions to the European Directive truck size and weight regulations, with the objective of adapting the directive to new technologies and needs, facilitating intermodal transport, and the overall reduction of energy consumption and emissions (European Commission, 2012). The impact assessment study is expected to be completed later in the year 2012. The main proposed revisions under investigation are (Jacob, 2012):

- Increasing length limits to improve the aerodynamic performance of heavy vehicles.
- Increasing length limits for the transport of 45-ft containers on articulated vehicles.
- Allowing higher truck size and weight limits for cross-border truck operations under bilateral agreement between trading countries.
- Increasing weight limits for 2-axle coaches and electric or hybrid trucks carrying batteries.
- Implementation of truck size and weight enforcement to improve compliance with the regulations.

3.4. NEED FOR A EUROPEAN BRIDGE FORMULA

Structural design in European Union Member States is harmonized through the Eurocodes, providing uniform levels of safety in construction across Europe and allowing the exchange of construction services. The Eurocodes are a set of ten European Standards ranging from EN 1990 (Eurocode 0) to EN 1999 (Eurocode 9) developed by the European Committee for Standardization (CEN) that contain technical structural rules for the design of buildings and civil engineering structures. Each Eurocode standard is composed of fixed parts, where Part 2 deals specifically with bridges. Eurocode EN 1991 Part 2 provides standards on traffic load models for bridge design. By March 2010, the Eurocodes replaced all national codes published by national standards bodies, while taking into account local differences through Nationally

Determined Parameters (NDPs) published in the National Annex referenced in the Eurocodes. (MPA, 2011) (Eurocodes Online, 2011)

The major concepts developed in the Eurocodes are: fundamental requirements (safety, serviceability, fire, and robustness), reliability differentiation, design working life, durability, and quality assurance. The approach of structural reliability is based on the semi-probabilistic method (limit-state performance design and partial factors method) (Eurocodes, 2011).

Currently the commercial motor vehicle size and weight of EU (European Union) member states are regulated by the European Council Directive 96/53/EC developed in 1996. The directive defines the maximum allowable gross vehicle and axle weights and dimensions for various vehicle types and configurations travelling internationally between member states. Although commercial vehicle size and weight limits are harmonized between EU countries for cross-border travel, each country may set separate higher weight limits, and in some cases larger dimension limits, for national (intrastate) travel.

European Modular System vehicles have also been introduced in Europe and implemented as pilot studies in Finland, Sweden, and some routes in the Netherlands. The difference in national weight limits across EU countries and the increasing demand for larger and heavier vehicles brings the need to ensure the structural integrity and service life of bridges (TML, 2008).

In addition, European truck size and weight limits are currently regulated through fixed prescriptive methods regardless of the vehicle performance. Countries are moving away from prescriptive methods and are implementing performance based standards, which regulate truck size and weight of vehicles based on their performance in terms of interaction with traffic and highway infrastructure. Bridge formulae can be a type of performance based method for limiting truck size and weight hence allowing more flexibility and innovation in vehicle design and operation resulting from various axle weights at different axle spacing.

A bridge formula would allow the consistent limitation of weights among EU countries under performance based standards, while ensuring the structural capacity of bridges by limiting the imposed stresses on the bridge. A EUBF could also allow for future truck size and weight evolutions over a long-term period, while preserving the existing stock of bridges, designed with past and current loading codes. (Moshiri et al., 2011)

4. BRIDGE LOAD ANALYSIS

This chapter outlines the research methodology and provides results for the comparison of international bridge formulae and analysis of truck size and weight data as it relates to the potential development of a European Bridge Formula.

4.1. METHODOLOGY

The analysis conducted in this research consists of two components: (1) comparison of international bridge formulae and (2) load effect of European Directive trucks. Figure 14 shows the outline of the analysis methodology. These two components are further described.

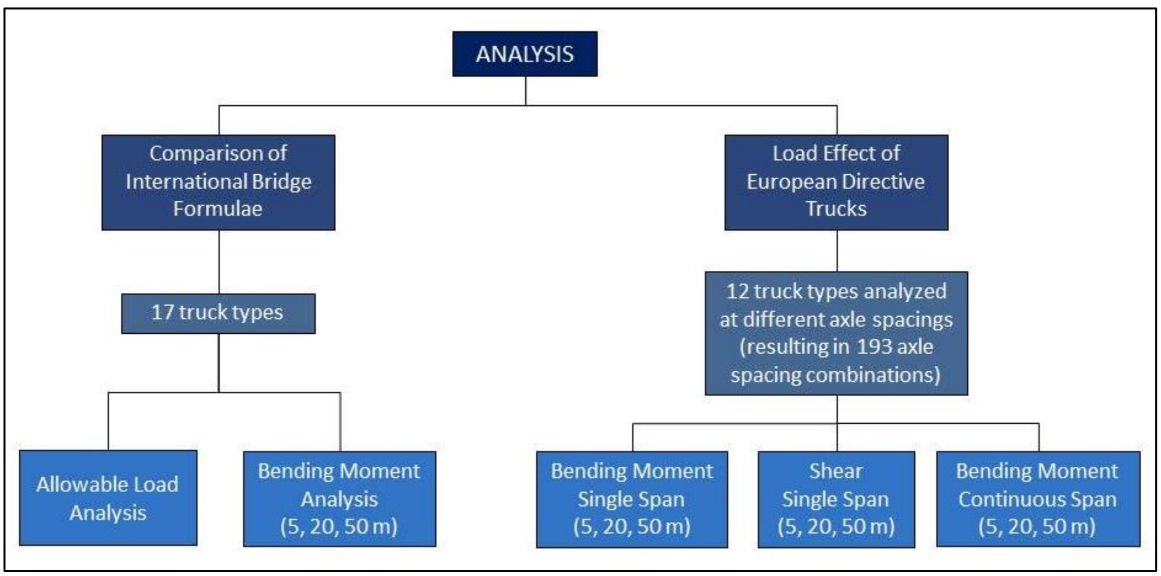
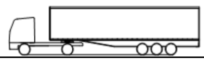
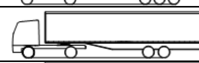
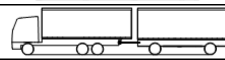
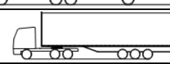
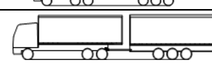
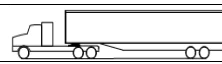
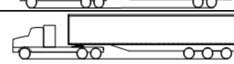
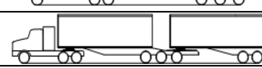
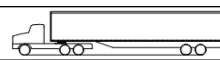
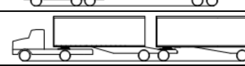
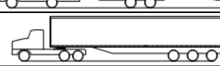
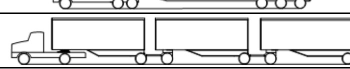


Figure 14: Research Analysis Methodology

4.1.1. Comparison of International Bridge Formulae

This task consists of two components: (1) allowable load analysis and (2) maximum bending moment analysis at mid-span for 5, 20, and 50-metre single span bridges. Each of these two components are analyzed for a series of 17 truck configurations, commonly used in the U.S., Canada, and Europe, complying with existing international bridge formulae. The truck configurations are identified in the study conducted by the Joint Transport Research Centre on Heavy Vehicles and are shown in Table 9 (ITF/OECD/JTRC, 2010).

Table 9: Vehicle configurations used for bridge formula comparisons

Truck Number	Truck Configuration	Wheelbase, metres
Europe reference		12.6
Europe 1		11.9
Europe 2		13.3
Europe 3		13.9
Europe 4		16.4
United Kingdom 1		13.3
United Kingdom 2		16.1
Canada 1		19.1
Canada 2		19.1
Canada 3		18.2
Canada 4		35.9
United Sates 1		17.3
United Sates 2		20.0
United Sates 3		17.5
United Sates 4		22.7
United Sates 5		29.1
United Sates 6		28.6

Source: adapted from ITF/OECD/JTRC, 2010

4.1.2. Load Effect of European Directive Trucks

The maximum bending moment and shear stresses imposed on bridges by European Directive truck crossings are evaluated for 12 truck configurations. Each configuration is analyzed at different axle spacings (minimum, mid, and maximum axle spacing limits specified in the European Directive 96/53/EC) resulting in 193 axle spacing combinations. The truck configurations are shown in Table 7 in Section 3.1 and all axle spacing combinations are shown in APPENDIX A. For every truck configuration, the axle spacing combination that results in the highest imposed stress is referred to as a worst case vehicle and the vehicle configurations with every axle spacing at mid-range are referred to as the reference vehicles.

Three critical load effect conditions are analyzed for each truck crossing, using influence lines that represent each condition and span length. The analyzed load effect conditions are:

- Bending moment stress at mid-span on single span bridges of 5, 20, and 50 metre spans
- Shear stress over the support on single span bridges of 5, 20, and 50 metre spans
- Bending moment over the support on continuous two span bridges of 5, 20, and 50 metre spans

The load effects imposed by the 193 axle spacing combinations are assessed for each of the critical stress conditions for 5, 20 and 50 metre spans. Each truck configurations is crossed along the 3 span lengths of each analyzed critical load condition at a set interval of 0.02 metres to determine the maximum load effect of every vehicle configuration for each condition and span length. Figure 15 shows the influence lines resulting from a unit load moving across a 20 metre span bridge for the three analyzed stress conditions. The load effect resulting from any other load (e.g. a five axle semi-trailer truck) crossing the span can be determined by the multiplication of the load by the influence line value (load effect) at any point on the span.

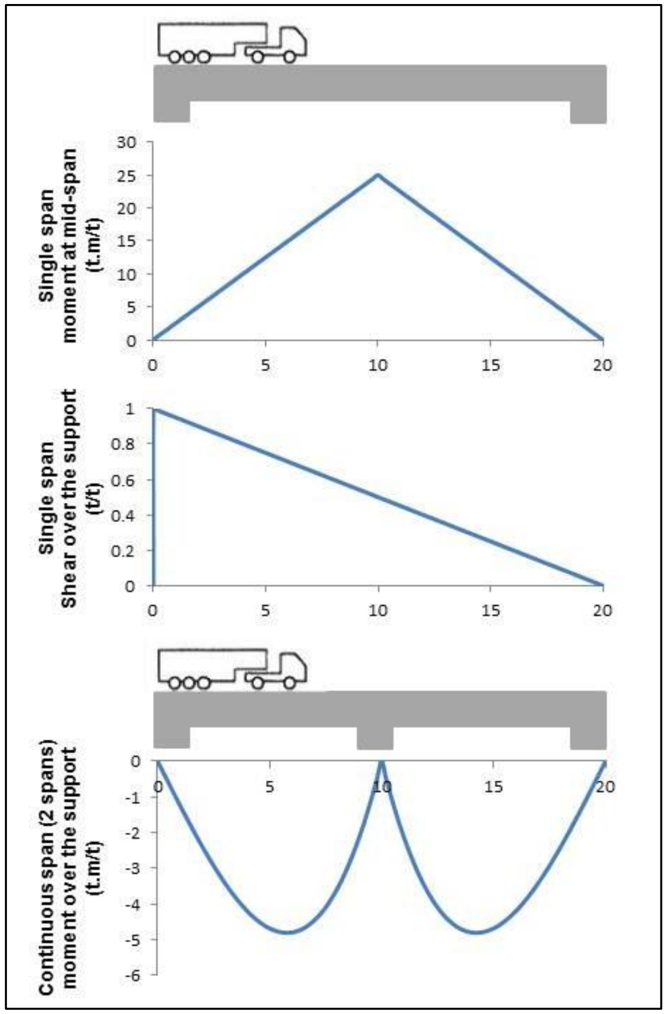


Figure 15: Bending moment influence lines for 20 metre span bridges
Source: developed by M.Moshiri

After assessing the load effects for each of the 193 axle spacing combinations, the aggressiveness of each combination is assessed relative to the European five axle standard reference truck (2-axle tractor and 3-axle semitrailer) with 40 tonnes GVW and 16.5 metres in length. The aggressiveness ratio is determined by comparing the maximum stress effect imposed by a specified vehicle with the maximum stress effect imposed by the standard reference vehicle. The aggressiveness ratios of the vehicles are compared to select the vehicles with acceptable aggressiveness for incorporation into the bridge formula.

The live load envelope is developed from the selected vehicles of acceptable aggressiveness. Various parameters, including axle spacing and number of axles, are evaluated to assess the level of impact of each parameter on the stress limits. This helps to determine the independent variables of the bridge formula.

The last step in the load effect analysis of the European Directive trucks is to determine relationships between the truck sizes and weights of the selected vehicles, following the format of the most common international bridge formulae. This is done with a view to developing a preliminary European Bridge Formula (EUBF) conforming to European truck configurations for the regulation of truck size and weight limits associated with international travel between European Union (EU) member states. The development criteria and assumptions in the development of truck size and weight relationships for a European bridge formula are described in the following sections.

Criteria for the Development of a European Bridge Formula

In the development of a European bridge formula, it was necessary that the resulting equation have the following characteristics:

1. Have a simple form to understand and use,
2. Conform to European trucks specified by the European Directive 96/53/EC and in future research to include the European Modular System (EMS) vehicles at 60t and 25.25m allowed in northern Europe,
3. Be applied to both internal and external axle spacings (inner and outer bridge),
4. Be in agreement with the design live loads specified in the Eurocode. The design loads include extrapolation of truck loads, the dynamic effect of truck loads, and load factors to account for the multiple presences of trucks and any uncertainties in the

load models, therefore the design loads are expected to be higher than those estimated by the bridge formula.

Assumptions for the Development of a European Bridge Formula

Five assumptions are made to limit the scope of analysis required for the development of this formula:

- The analyzed critical load effects are: (1) bending moment at mid-span of single span bridges, (2) shear force over the support of single span bridges, and (3) bending moment over the support of continuous two span bridges.
- There is one lane loading only, therefore not taking into account the effects of possible side by side loading of trucks.
- The analysis involves the load effect of Individual truck crossings, and not the cumulative effect of a platoon of heavy trucks.
- The analysis does not take into account the bridge material (i.e., concrete or steel). Theoretical influence lines are used for the analysis of load effects, while acknowledging actual influence lines may be different.
- The effect of fatigue is not considered in the development of the bridge formula. The formula should be checked for fatigue to ensure the serviceability of bridges are within acceptable limits.

4.2. TOOLS FOR ANALYSIS

Pollux, a software developed by LCPC in 2007, is used to determine the load effects imposed by trucks traversing a bridge. The program inputs are influence line data files and traffic data files. The influence line data files are the load effects at one point on the bridge as a unit action moves along the bridge span. The program is designed to assess the cumulative effect of Weight in Motion (WIM) traffic data on the influence lines; however this research is limited to the analysis of individual truck crossings. Therefore, individual data files are created for each truck configuration with varying axle spacings (i.e., 193 axle spacing combinations), complying with the WIM data file format. An example of the traffic data input format for a three axle single unit truck used in this research is shown in Figure 16.

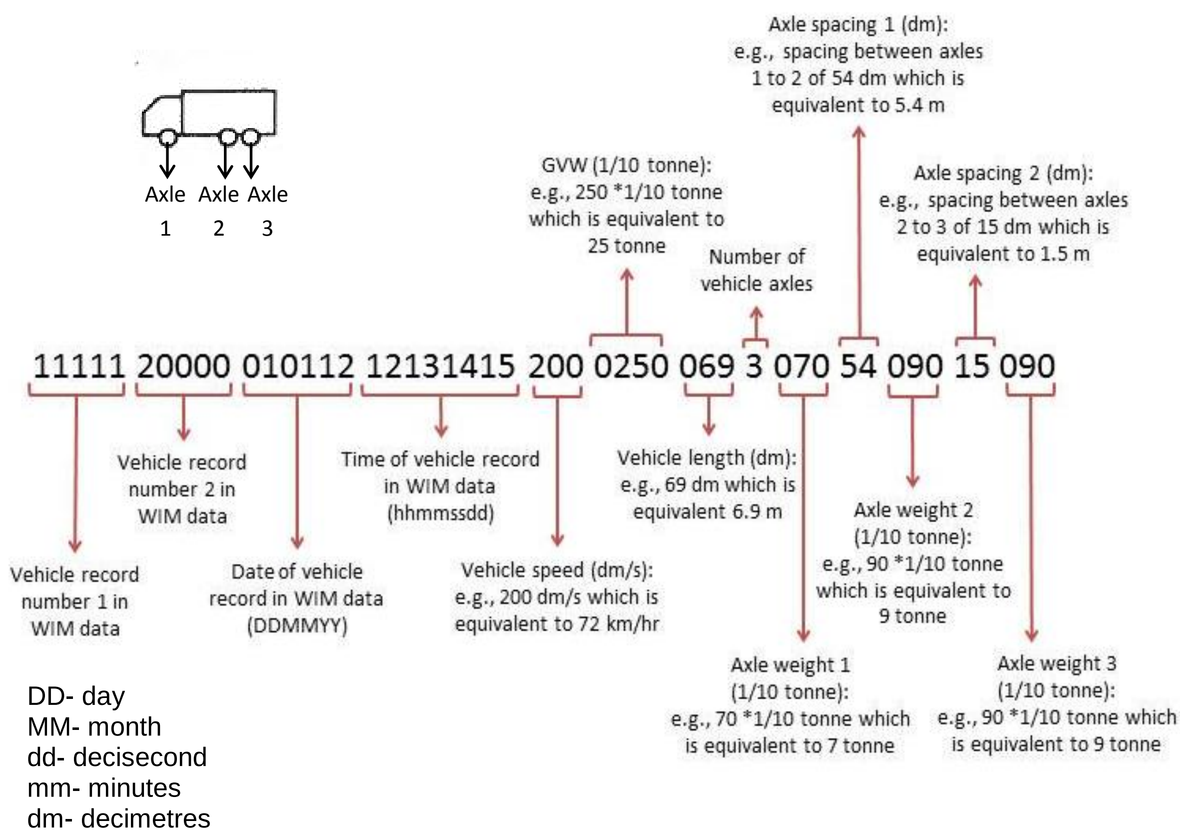


Figure 16: Pollux vehicle data input format example
(Adapted from: Koubi and Schmidt, 2010)

The traffic data and the units used by Pollux are:

- the vehicle number (five characters)
- date (DDMMYY)- day, month, year
- hour (hhmmssdd)- hour, minute, second, deci-second

- speed (decimetre per second, three characters)
- loads: GVW (one tenth of a tonne, four characters) and per axle (one tenth of a tonne, three characters)
- lengths: total vehicle (decimetre, three characters) and axle spacing (decimetre, two characters)

Once the traffic data and influence line data files are inputted into Pollux, the software has the ability to conduct the following functions:

1. *WIM traffic data screening:*
    - Removal of errors: The user can set maximum and minimum limits on parameters such as speed, length, GVW, axle load, number of axles, distance between axles, and time gap in data (time between each vehicle record) to identify acceptable data within these set limits. Based on the set parameter limits, the program identifies and removes data assumed to be false in an input WIM data file, such as a vehicle record with an abnormally high length or weight value that may be due to the amalgamation of two vehicles (or trucks) into one vehicle recording.
    - Removal of light vehicles: The user can allow the program to remove light vehicles from the analysis by setting the parameters (maximum number of axles and GVW) that define light vehicles. This is useful for removing passenger vehicles from a WIM traffic data file to allow the analysis of heavy vehicle load effects.
    - Setting uniform speeds: The user can restrict the passing of vehicles or overlapping of vehicles in one lane traffic data files by setting a constant speed for all vehicles in the WIM data file. The user can also create congested traffic situations by setting the distance between vehicles.

- Multi-lane traffic data retrieval: The program can assemble different one lane traffic data files to obtain a multilane traffic data file.
- Creation of histograms: The program can create histograms for the traffic data (all vehicles or trucks only) showing the number of vehicles categorized by distance between vehicles, number of truck axles, speeds, GVW, and axle loads.

2. *Assessing the effects of the traffic data on the influence lines*: The effect of one chosen traffic data file on one selected bridge influence line is conducted at a time. The user can set the time interval for the program to record results, for example readings every 0.01 seconds.

3. *Assessing the effects of fatigue:* The fatigue damage caused on the bridge by the traffic data per week, over a number of selected years, and the lifetime of the bridge can be calculated. Fatigue damage calculations are not conducted in this research.

For this research, the stresses imposed by individual vehicle configurations traversing each bridge type and span length (5 m, 20 m , and 50 m) are assessed to determine the maximum load effect of each of the 193 vehicle configurations on each bridge type and span.

The software data inputs within the scope of this research are:

- individual vehicle data files consisting of the vehicle characteristics (as shown in Figure 16).
- influence lines for both single and continuous span bridges of 5, 20, and 50 meter span lengths.

Pollux has limitations that do not allow the evaluation of all vehicle configurations. The software allows the input of one digit values for the number of axles and two digit values for axle spacing in decimetre units. This limitation does not allow the evaluation of vehicles with over 9 axles and 9.9 meter axle spacing. For instance, an axle spacing of 12.5 meters would have to be inputted as a three digit number of 125 dm, which is over the two character limit. In some cases, where the vehicle has eight or lower number of axles, an additional axle carrying zero weight is placed between the two axles to divide the spacing to a lower two digit value in decimetre units.

4.3. COMPARISON OF INTERNATIONAL BRIDGE FORMULAE

The various existing bridge formulae have been developed and applied differently by jurisdictions, and have varying characteristics in terms of the format, parameters (e.g., number of axles, axle spacing), constraints (e.g., truck length limit, gross vehicle and axle weight limits), and application method (e.g., route class specific, applied to inner and/or outer axle groups).

The level of restrictiveness of the truck size and weight limits set by each jurisdiction vary significantly depending on the type of infrastructure, bridge design methods, bridge design loads, existing truck configurations, commodity type demand, and politics of the jurisdiction. In principle, higher capacity bridges should be permitted to support higher operating loads.

Bridge design methods and design loads are typically the basis for bridge formula development and may impact the level of restrictiveness of bridge formulae. The majority of the U.S. Interstate Highway bridges have been designed to an AASHTO HS20 live load model, representing a tractor semitrailer truck at 72,000 lb. To account for heavier loads, some states use HS25 loads, 25 percent larger than HS20 loads. In Canada, bridges are designed to the CL-625 live load model (5-axle truck at 140,456 lb) specified in the CAN/CSA-S6 Canadian highway bridge design code, and the Ontario Highway

Bridge Design (OHBD) live load (5-axle truck at 166,400 lb) within Ontario. The OHBD design vehicle is based on a survey of maximum observed overloads and multiplied by a live load factor of 1.4, whereas the CAN/CSA-S6 design vehicle is based on regulatory loadings and is multiplied by a higher live load factor of 1.6 to account for potential overloads. (Woodrooffe et al., 2010)

All three load models (HS20, CL-625, and OHBD design loads) are applied differently in terms of superimposing lane loads, dynamic load allowances, and load factors used in the load factor design (LFD). Figure 17 shows the resulting factored bending moment stresses from the U.S. and Canadian design loads, including the dynamic impact factors. In the end, the two Canadian bridge design loads (CL-625 and OHBD design loads) result in similar bending moments on single span bridges. Canadian bridges, based on both design models, are designed for significantly higher loads than the U.S. bridges, with the exception of the CL-625 load model for short span bridges up to 15 metres. The factored design moments of OHBD and CL-625 loads are up to double that for HS20 loads for 45 metre simple span bridges. (Woodrooffe et al., 2010)

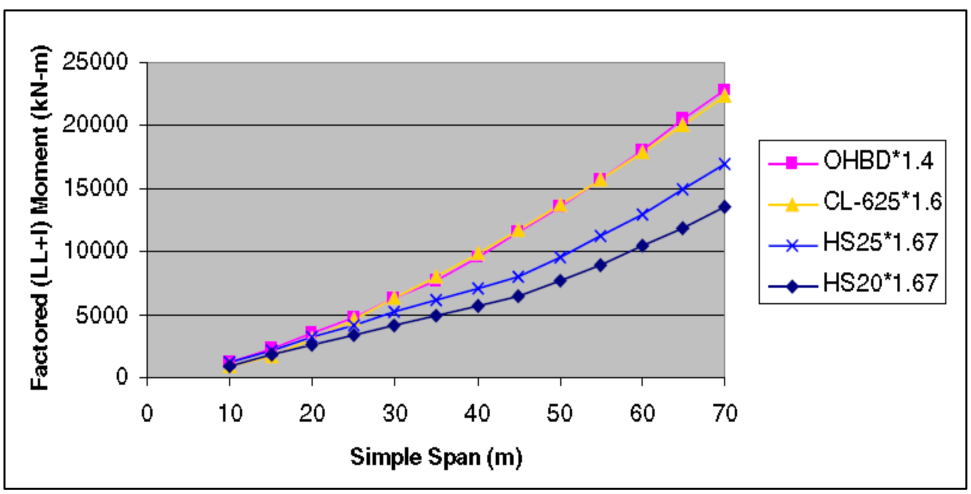


Figure 17: Factored Design Moments by Canadian and HS Design Vehicles on Simple Spans
(Source: Woodrooffe et al., 2010)

The design live loads in Mexico are also larger than the U.S. design live loads, resulting in a more permissive Mexican bridge formula relative to the U.S. BFB. The bridge design live load used in Mexican bridge design for class ET (Transportation Axis Highways-highest category of roadways in Mexico), A, B, and C highways as specified in the Transportation Infrastructure Regulations published by the Secretaria de Comunicaciones y Transportes (SCT), is a six-axle vehicle with a total GVW of 146,607 lb and total overall length of 49.7 feet. (Middleton, et al. 2011)

The difference in bridge design methods and loads are evident amongst countries. The level of restrictiveness of the bridge formulae are compared in terms of allowable weights and load effect on bridges, while keeping in mind the differences in infrastructure capacity and truck fleet characteristics.

As previously indicated, this part of the analysis is composed of two components: (1) allowable load analysis and (2) bending moment analysis at mid-span for 5, 20, and 50-metre single span bridges.

4.3.1. Allowable Load Analysis

Applying a bridge formula to the outer axles of the vehicle (i.e., the wheelbase between the first and last axles) determines the allowable gross weight of the vehicle. Figure 18 presents the gross weights determined by different bridge formulae on a series of 17 truck configurations commonly used in the United States, Canada, and Europe. The truck configurations are identified in the study conducted by the Joint Transport Research Centre on Heavy Vehicles (ITF/OECD/JTRC, 2010) and are shown in Table 9.

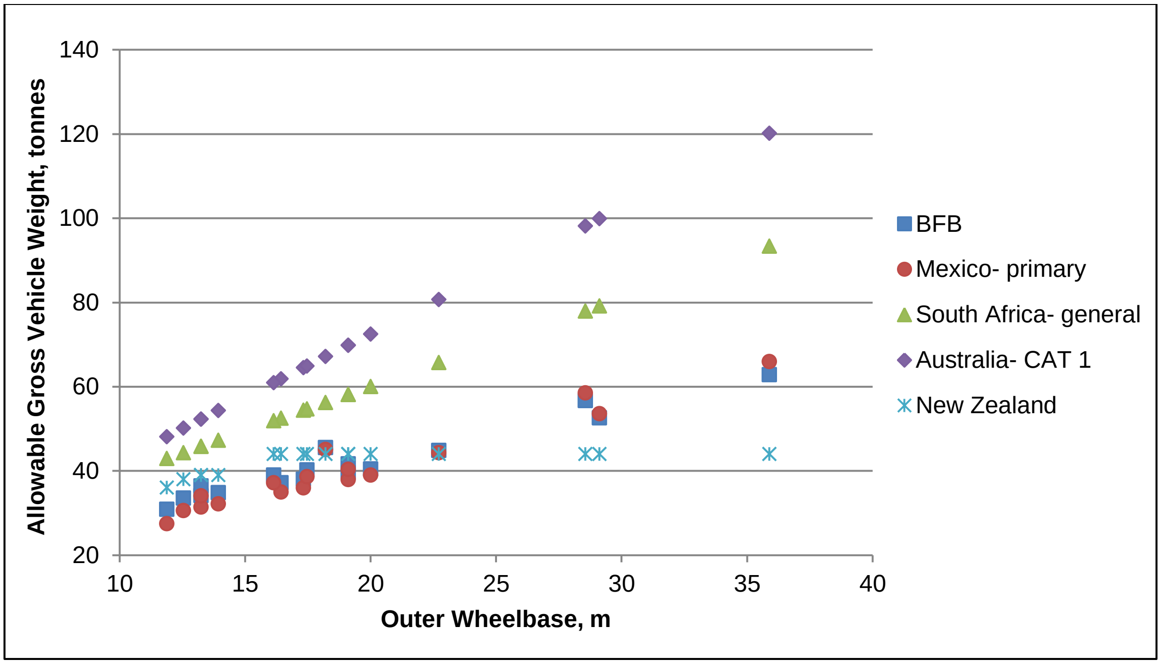


Figure 18: Allowable Gross Weights by bridge formulae applied to outer axles only

The level of restrictiveness of the different bridge formulae are shown in Figure 18. The Australian bridge formula used for limiting weights on general access vehicles and road trains on Category 1 routes is the most permissive, followed by the South African bridge formula. For the analyzed truck configurations, the BFB and Mexican bridge formula allow the lowest gross vehicle weights up to the truck configuration with 18.2 meter wheelbase, where the New Zealand bridge formula becomes the most restrictive after this outer wheelbase distance due to the 44 tonne limit.

The bridge formulae used in the U.S., Canada, South Africa, New Zealand, and Australia must also be applied to all internal axle combinations. Complying with the allowable load limits on all internal axle combinations may result in a lower allowable GVW for some truck configurations. Figure 19 shows what the allowable GVW on a Canadian five axle truck with 19.1 metre wheelbase would be, with the outer bridge or inner bridge complying with different bridge formulae. It is important to note that this scenario applies only to GVW and does not take into consideration any restrictions resulting from axle loads.

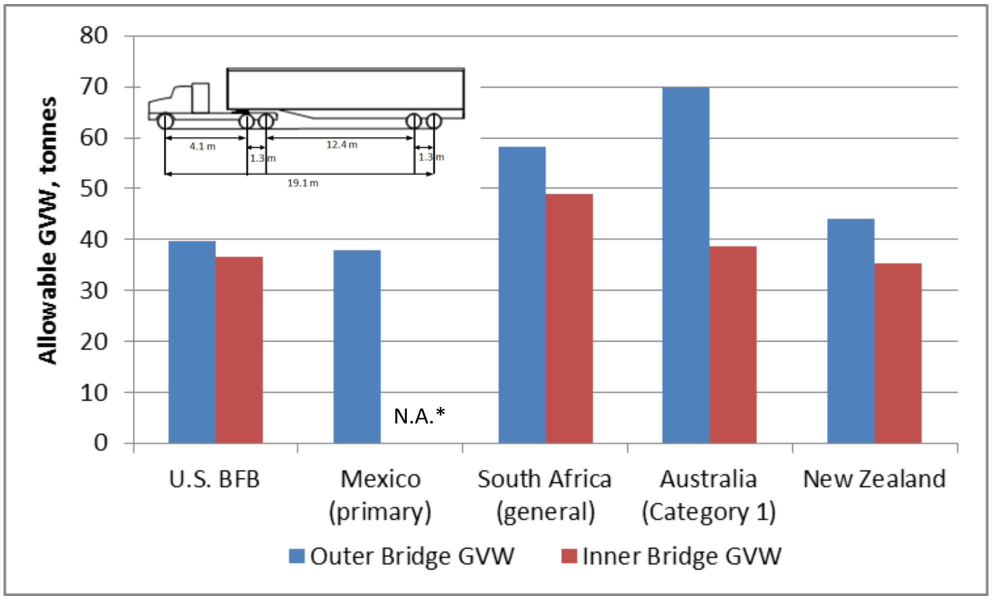


Figure 19: Allowable Inner and Outer Bridge GVW for a Canadian Five Axle Truck by Bridge Formulae
* Mexican bridge formula is applied to outer bridge only for GVW restrictions

Figure 20 shows the actual allowable gross weights that the vehicles can carry if the bridge formulae are applied to all consecutive axle combinations. The allowable gross vehicle weights are reduced in most cases when the bridge formula is applied to all axle combinations relative to applying the bridge formulae only to the external axles. This shows that allowing the gross vehicle weights determined by applying only the outer bridge formulae may result in axle loads that exceed the overstress criteria used in the development of these bridge formulae.

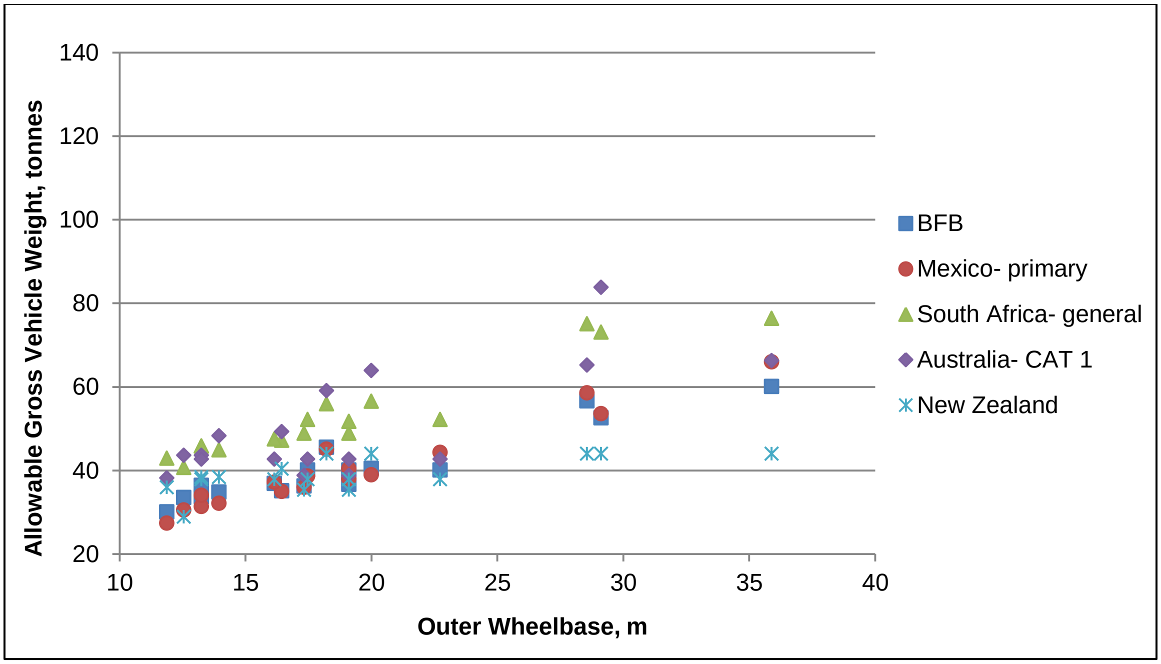


Figure 20: Allowable gross weights by bridge formulae applied to all axle combinations

4.3.2. Bending Moment Analysis

The load effects for the same selection of 17 European and North American vehicle configurations are determined based on the bridge formula weights applied to all axle combinations and the typical steering axle weight used in each country. Figures 21, 22, and 23 compare the maximum bending moment at mid-span for a single span bridge of 5, 20, and 50 metre spans, respectively.

The Figures show that the relative restrictiveness comparison of the bridge formulae in terms of the allowable loads is similar to the relative load effect comparison of bridge formulae in terms of bending moments, where in most cases, the bridge formulae allowing higher weights impose higher load effects on the bridge. The Australian and South African bridge formulae impose the highest load effects. The significant variation in the level of allowable loads and load effects may be due to the variations in the bridge design methods and design loads. Higher design loads and safety margins may allow higher loads on bridges, which may lead to higher load effects on bridges.

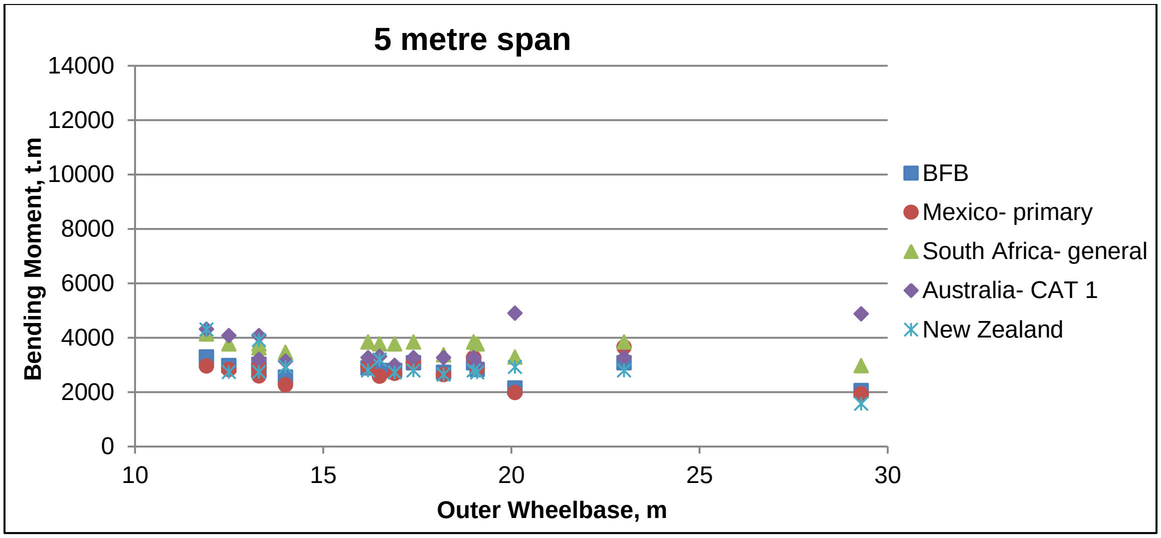


Figure 21: Maximum bending moment at mid-span for 5 metre single span bridge

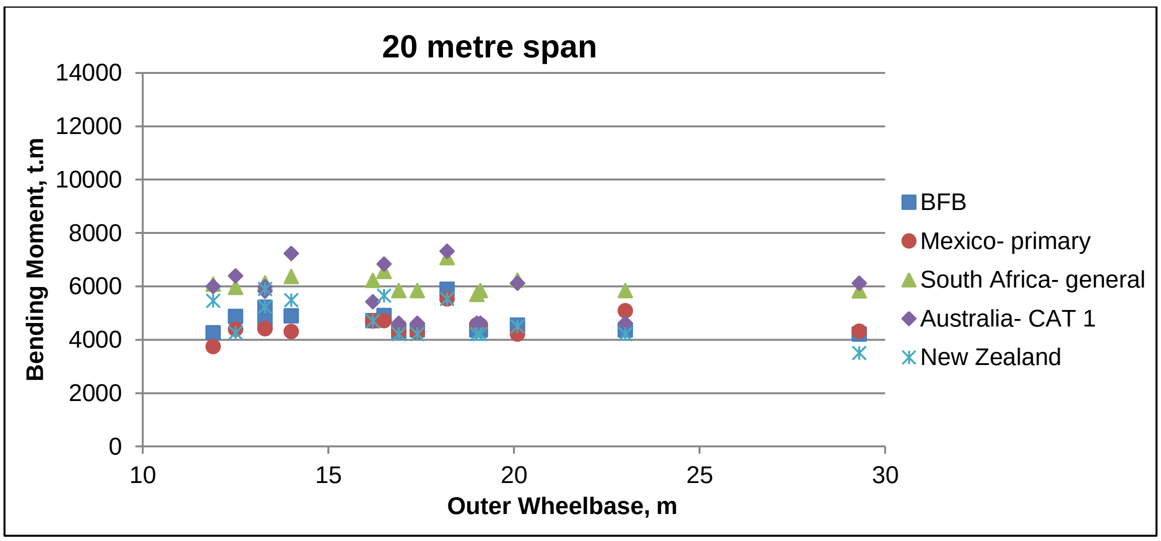


Figure 22: Maximum bending moment at mid-span for 20 metre single span bridge

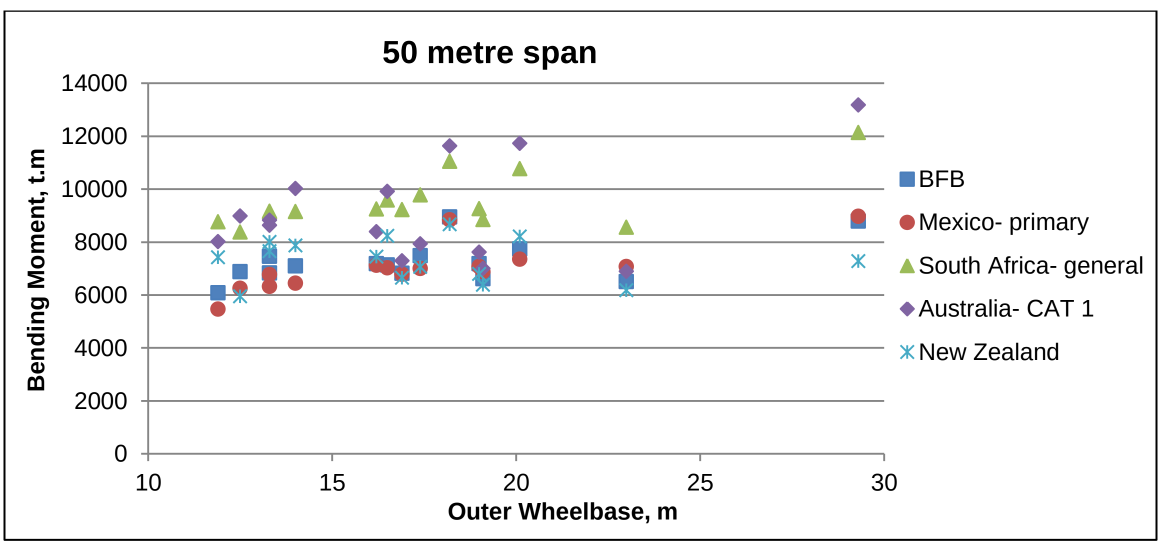


Figure 23: Maximum bending moment at mid-span for 50 metre single span bridge

Figure 24, Figure 25, and Figure 26 show an individual vehicle comparison example in terms of the mid-span bending moment stresses on single span bridges imposed by the five axle reference vehicles from Europe (16.5 m length and 13.3 m wheelbase), Canada (21.6 m length and 19.1 m wheelbase), and the U.S. (19.8 m length and 17.3 m wheelbase) respectively. The imposed load effect of the European reference truck configuration (2-S3) is generally higher relative to the Canadian and U.S. reference truck configurations (3-S2) for all bridge formula allowable weights, except for the Mexican bridge formula. This is because the tridem axle on the European vehicle is allowed to carry higher weights relative to the tandem axle on the Canadian and U.S. vehicles, which imposes higher stresses. The Mexican bridge formula however is only applied to the outer wheelbase of the vehicle and not to the inner axle group combinations, therefore allowing higher weights on the vehicle with the longer wheelbase. Thus, in the case of the Mexican bridge formula, the imposed stresses are slightly lower for the European truck configuration relative to the Canadian and U.S. truck configurations.

The imposed load effects by the U.S. and Canadian reference trucks are similar, with the U.S. truck imposing slightly higher load effects in most cases. This is because the U.S. and Canadian reference trucks are of the same configuration (3-axle tractor and 2-axle semitrailer), however the Canadian truck has a longer wheelbase of approximately 2 metres. The longer wheelbase allows a higher GVW when a bridge formula is applied to the extreme outer axles; however, the internal axle groups (such as the tandem axles) are restricted to the same weight limits due to the same internal axle configuration of two tandem axles on both vehicles. This results in the same load being distributed over a longer length on the Canadian truck, therefore imposing lower load effects.

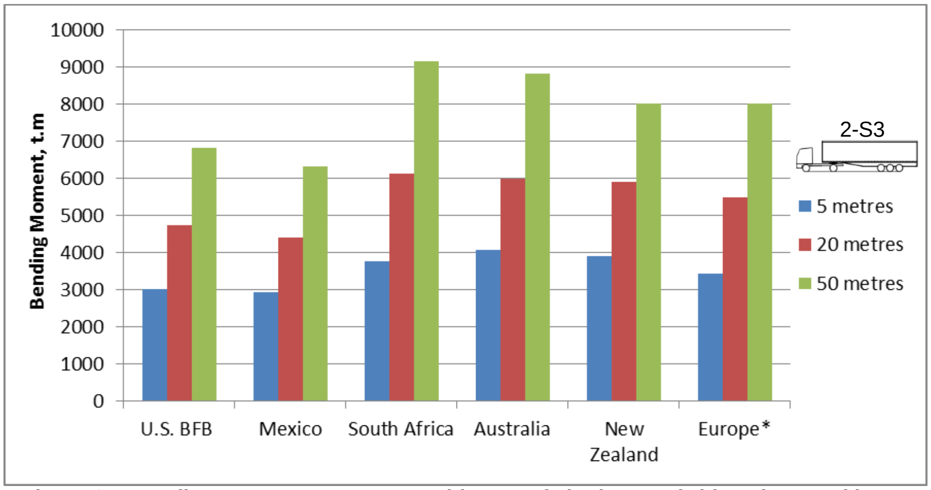


Figure 24: Bending moment stresses at mid-span of single span bridges imposed by European reference truck configuration conforming to international bridge formulae
* Using actual allowable gross vehicle and axle weights in Europe

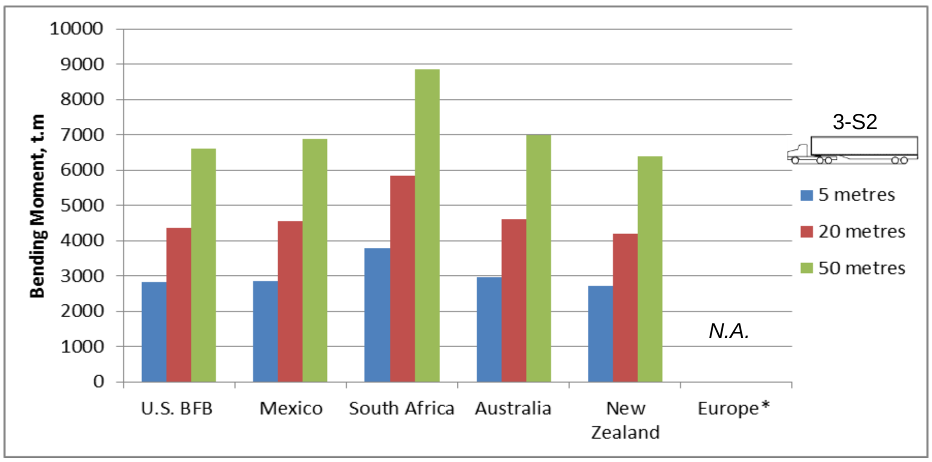


Figure 25: Bending moment stresses at mid-span of single span bridges imposed by Canadian reference truck configuration conforming to international bridge formulae
* Not a practical truck in Europe

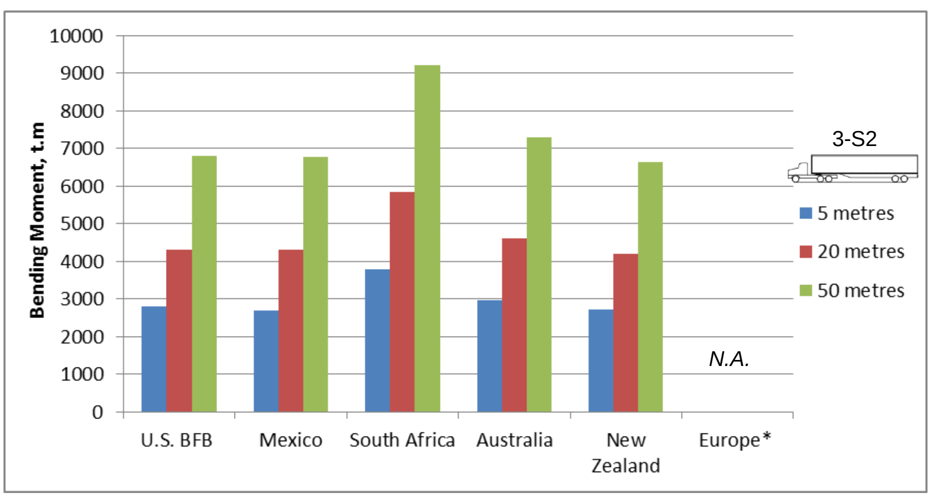


Figure 26: Bending moment stresses at mid-span of single span bridges imposed by U.S. reference truck configuration conforming to international bridge formulae
* Not a practical truck in Europe

Figure 24, Figure 27, Figure 28, and Figure 29 compare the mid-span bending moment stresses on single span bridges imposed by practical European truck configurations shown in Table 9, conforming to different international bridge formulae and their actual allowable weights in Europe.

The South African and Australian bridge formulae impose the highest load effects on single span bridges due to higher allowable gross vehicle and axle loads. It is noticed that the Australian bridge formula imposes higher stress levels on the longer vehicles (T2-3 and T3-2) relative to the tractor-semitrailers. The imposed load effects by the actual European gross vehicle and axle weights are higher than the U.S. and Mexican allowable loads due to the restrictiveness of the U.S. and Mexican bridge formula allowable loads.

The highest actual load effect (i.e. load effect due to European actual weights) on 20 and 50-metre span bridges is imposed by the 3-axle truck and 2-axle trailer combination (T3-2), indicating that this is the most aggressive practical European vehicle, although all four practical European truck configurations impose relatively similar load effects of approximately 8,000 t.m. However, the 4-axle tractor-semitrailer (2-S2) imposes the highest load effect on 5-metre span bridges. A 5-metre span bridge is governed by the axle group loadings that can be on the span at the same time. The 4-axle tractor semi-trailer has the highest axle group loading of 10 tonnes per axle on the rear tandem axle. Whereas the 3-axle truck and 2-axle trailer combination has lower axle loadings for axle groups that can be on a 5-metre span at once, for example a tandem axle loading of 9 tonnes per axle and a trailer two axle group loading of 7.5 tonnes per axle.

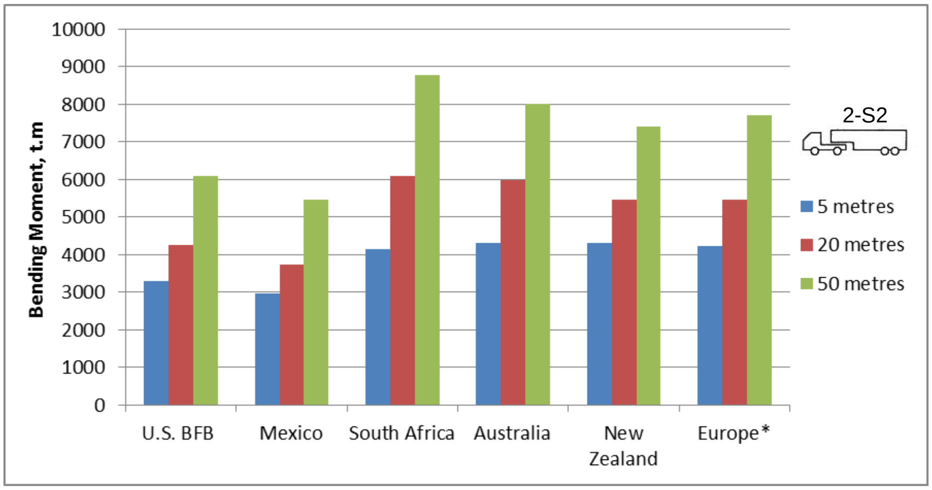


Figure 27: Bending moment stresses imposed by European four axle tractor-semitrailer conforming to international bridge formulae at mid-span of single span bridge
* Using actual allowable gross vehicle and axle weights in Europe

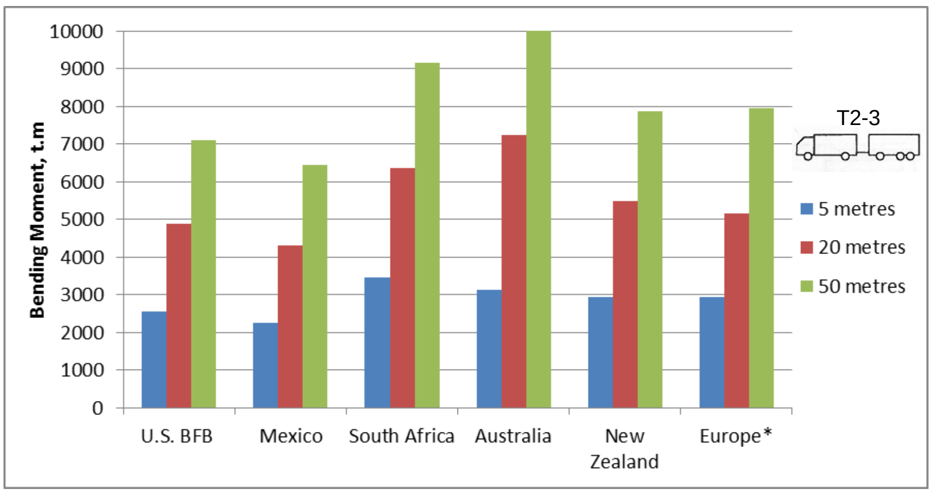


Figure 28: Bending moment stresses imposed by European five axle truck-trailer combination conforming to international bridge formulae at mid-span of single span bridge
* Using actual allowable gross vehicle and axle weights in Europe

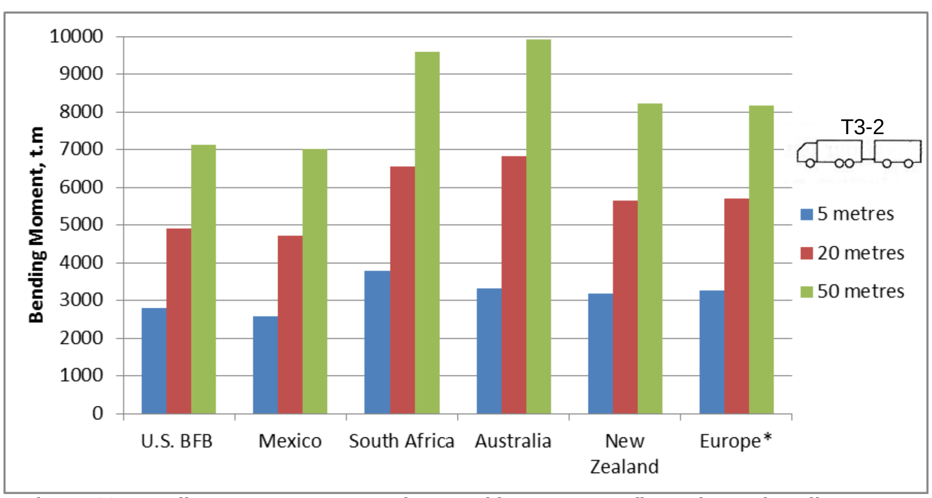


Figure 29: Bending moment stresses imposed by European five axle truck-trailer combination conforming to international bridge formulae at mid-span of single span bridge
* Using actual allowable gross vehicle and axle weights in Europe

4.3.3. Observations from Comparison of International Bridge Formulae

Observations from the comparison of international bridge formulae in terms of allowable weights and their imposed bridge stresses are:

- The varying levels of restrictiveness of existing bridge formulae can be noticed through the comparison of the allowable weights and imposed load effects on bridges. The bridge formulae imposed the highest bending moments when the highest gross vehicle weights were allowed. The significant variation in the level of allowable loads and resulting load effects of the different international bridge formulae may be due to the variations in the bridge design methods and design loads.
- When applying the bridge formulae to the outer bridge of vehicles, the Australian bridge formula used for limiting weights on general access vehicles and road trains on Category 1 routes is the most permissive, followed by the South African bridge formula. In accordance, these bridge formulae impose the highest bridge load effects, in terms of bending moment at mid-span. For the analyzed truck configurations, the BFB and Mexican bridge formula allow the lowest gross vehicle weights up to length of 20 metres. Beyond this length, the New Zealand bridge formula becomes the most restrictive due to the 44 tonne limit.
- Based on the allowable load analysis, applying a bridge formula to all axle group combinations reduces the allowable gross vehicle weight relative to applying it to outer axles only, depending on the truck configuration. The higher allowable weight of applying a bridge formula to only the outer axles of a vehicle without satisfying inner axle group weight limits may allow axle loads on bridges that exceed the overstress criteria that were used in the development of the bridge formula

- In addition to the bridge formula itself, the truck configurations impact the allowable weights and imposed load effects. For example, the European and North American standard reference trucks are 5-axle tractor-semitrailers, however with different axle group configurations. The imposed load effect of the European reference truck configuration (2-S3) is generally higher relative to the Canadian and U.S. reference truck configurations (3-S2) for the international bridge formula allowable weights.
- The imposed load effects by the actual European gross vehicle and axle weights are higher than the U.S. and Mexican allowable loads due to the restrictiveness of the U.S. and Mexican bridge formula allowable loads.
- The highest load effect imposed by European actual weights on 20 and 50-metre span bridges is imposed by the 3-axle truck and 2-axle trailer combination (T3-2), indicating that this is the most aggressive practical European vehicle. However, the 4-axle tractor-semitrailer (2-S2) imposes the highest load effect on 5-metre span bridges.

4.4. ANALYSIS OF TRUCK SIZE AND WEIGHT DATA FOR THE DEVELOPMENT OF A EUROPEAN BRIDGE FORMULA

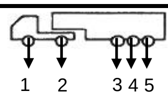
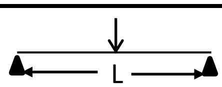
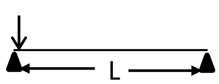
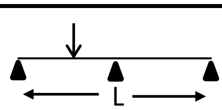
This is the second component of the research analysis, as discussed in Section 4.1.2. The analysis of the European truck size and weight regulations and the imposed load effects on bridges is conducted with a view to identifying issues and providing the basis for developing a European bridge formula.

The general methodology to providing preliminary EU bridge formula (EUBF) relationships is to determine the load effect of each European Directive vehicle configuration, resulting in 193 axle spacing combinations, on the various bridge types (single and continuous spans) and bridge spans (5, 20, and 50 metres). The EUBF must take into account the critical effect of all combinations of selected European trucks and bridge types. The critical load effects, in the scope of this research, include bending moments and shear at mid-span and over support for single and continuous span bridges. Further analysis must be conducted on the development of a EUBF to consider additional factors to overstressing of bridges, including fatigue effects, effect on pavements, presence of multiple vehicles and multiple lane loadings. However, this is beyond the scope of this research.

4.4.1. Data Analysis

The data analysis shows relationships for stresses imposed by (1) all European Directive vehicles (193 axle spacing combinations), (2) reference vehicles only (12 axle spacing combinations), and (3) worst case and reference vehicles (12 reference axle spacing combinations and greater than 12 worst case axle spacing combinations for each load effect and bridge span due to different axle spacings resulting in the same worst case load effect). For every truck configuration, the axle spacing combination that results in the highest imposed stress is referred to as a worst case vehicle and the vehicle configurations with every axle spacing at mid-range are referred to as the reference vehicles. More than one axle spacing combination for each of the 12 truck configurations can result in worst case stresses on 5 metre span bridges. This is because all truck axles cannot be on the five metre span at one time, and varying axle group configurations could result in the same worst case bending moment stresses. For example, Table 10 shows the reference vehicle and the worst case axle spacing combinations for the evaluated bridge load effect conditions for a European five axle reference vehicle. The arrows represent the location of single axle loads that would impose the highest stress for the analyzed critical condition. In this example, two axle spacing combinations result in the same worst case mid-span bending moment on a five metre single span bridge.

Table 10: Reference and worst case axle spacing combinations for a European 5-axle reference truck

	**Span length (L), metres**	**Axle Spacing, metres**			
		Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**	**Axle 4 to 5**
Reference vehicle	N.A.	3.6	7.1	1.3	1.3
Worst case*:					
 Bending moment at mid-span	**5**	4.5	3.6 or 8.6	0.6	0.6
	20	3.2	3.6	0.6	0.6
	50	3.2	3.6	0.6	0.6
 Bending moment over the support	**5**	4.5	3.6	0.6	0.6
	20	3.2	3.6	0.6	0.6
	50	3.2	3.6	0.6	0.6
 Bending moment over the pier	**5**	4.5	8.6	0.6	2.4
	20	3.2	8.6	0.6	0.6
	50	3.2	3.6	0.6	0.6

* Worst case vehicles are those with axle spacing combinations that result in the highest imposed stresses for each load effect condition

4.4.1.1. All vehicle stresses

The maximum stresses imposed by the European Directive vehicle configurations (193 axle spacing combinations) are analyzed for 5, 20, and 50 metre span bridges for the three evaluated critical conditions of single span at mid-span, single span over the support, and continuous span over the support. The twelve truck configurations are shown in Table 7 and all axle spacing combinations are shown in APPENDIX A. Figure 30, Figure 31, and Figure 32 show the maximum bending moment stresses imposed by each truck configuration, with varying axle spacing combinations, at the mid-span of 5, 20, and 50 metre single span bridges, respectively, as a function of the vehicle wheelbase. Figure 33, Figure 34, and Figure 35 show the maximum shear stresses imposed by vehicles over the support of 5, 20, and 50 metre single span bridges respectively, and Figure 36, Figure 37, and Figure 38 show the maximum bending moment stresses imposed by vehicles over the support of 5, 20, and 50 metre continuous span bridges respectively.

The Figures show declining imposed stresses for each truck configuration with increased vehicle lengths for constant weights on 20 and 50 metre span bridges, while increasing GVWs result in increased imposed stresses. Overall vehicle lengths of over 5 metres do not affect the imposed stresses on the short span bridge of 5 metres, as shown in the Figures, where the entire length of the vehicle is not on the bridge at one time. However, axle spacing can have an impact on the imposed stresses since axle groups can be on the span at the same point in time. The load effects range from 2,040 to 8,845 t.m for bending moment stresses at mid-span, 79 to 366 tonnes for shear stress over the support, and 424 to 1,785 t.m for bending moment stresses over the support.

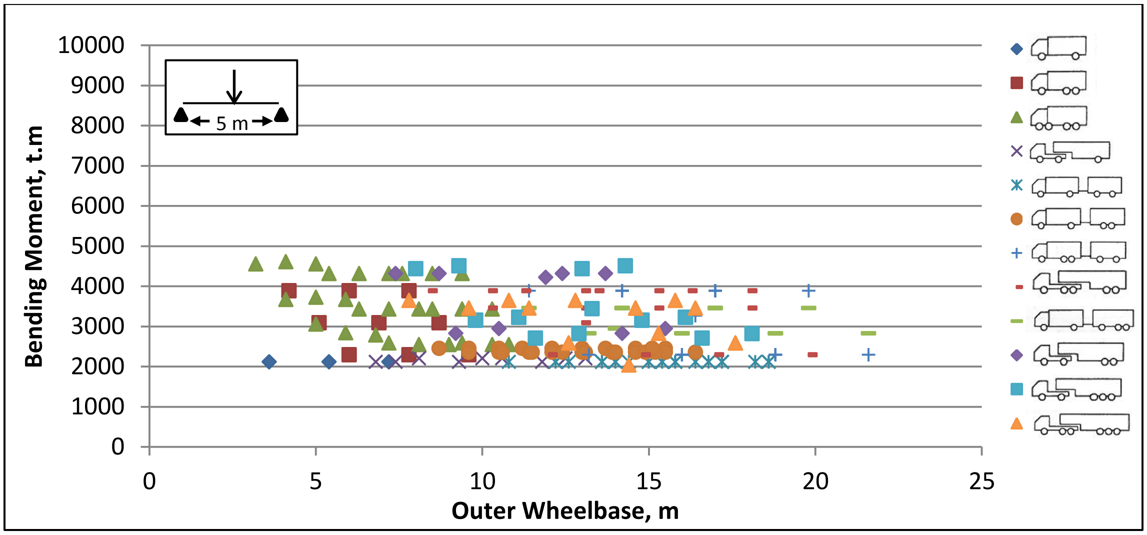


Figure 30: Bending moment stresses on a 5 metre single span bridge at mid-span

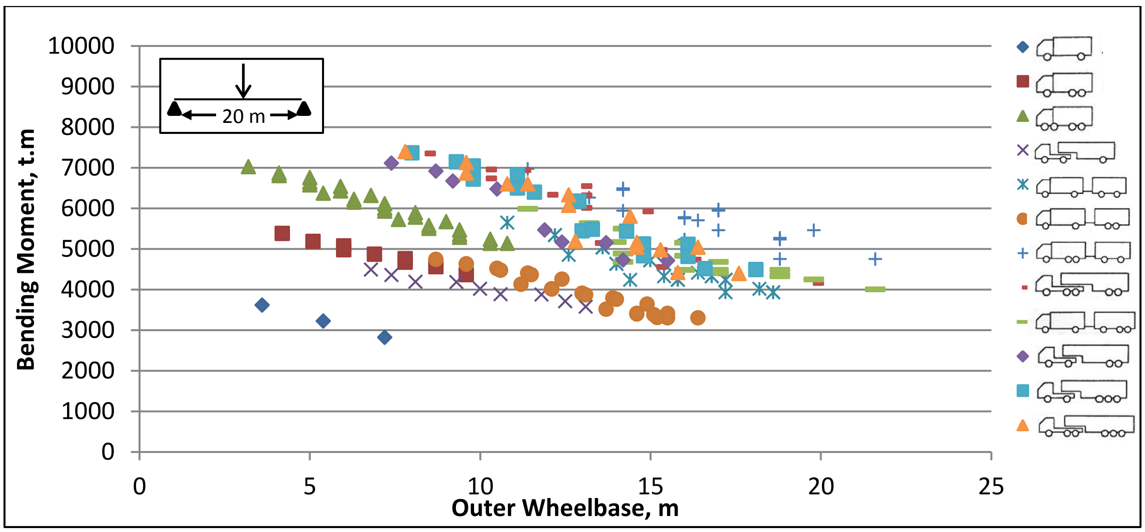


Figure 31: Bending moment stresses on a 20 metre single span bridge at mid-span

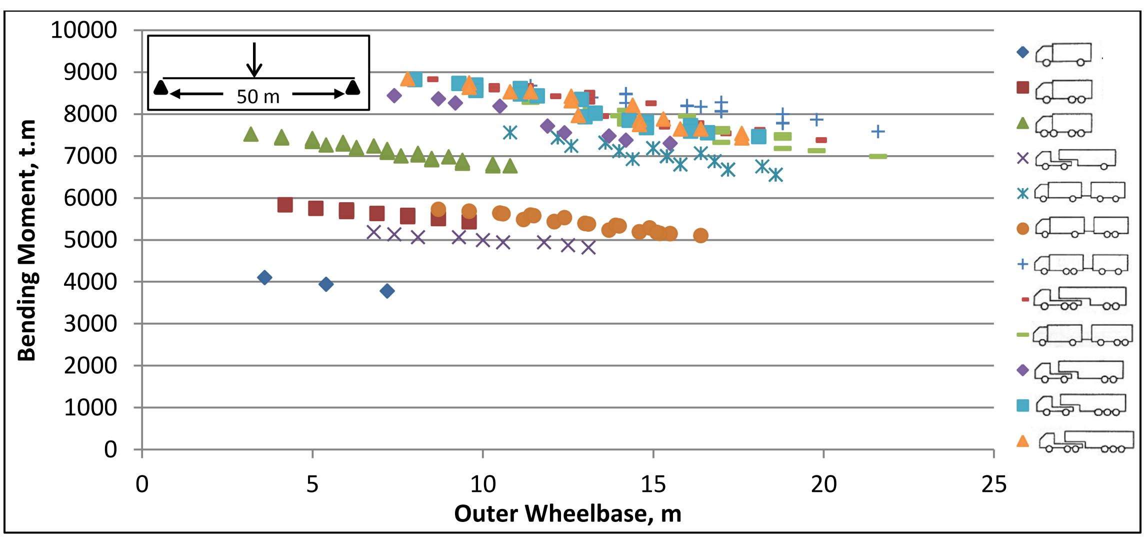


Figure 32: Bending moment stresses on a 50 metre single span bridge at mid-span

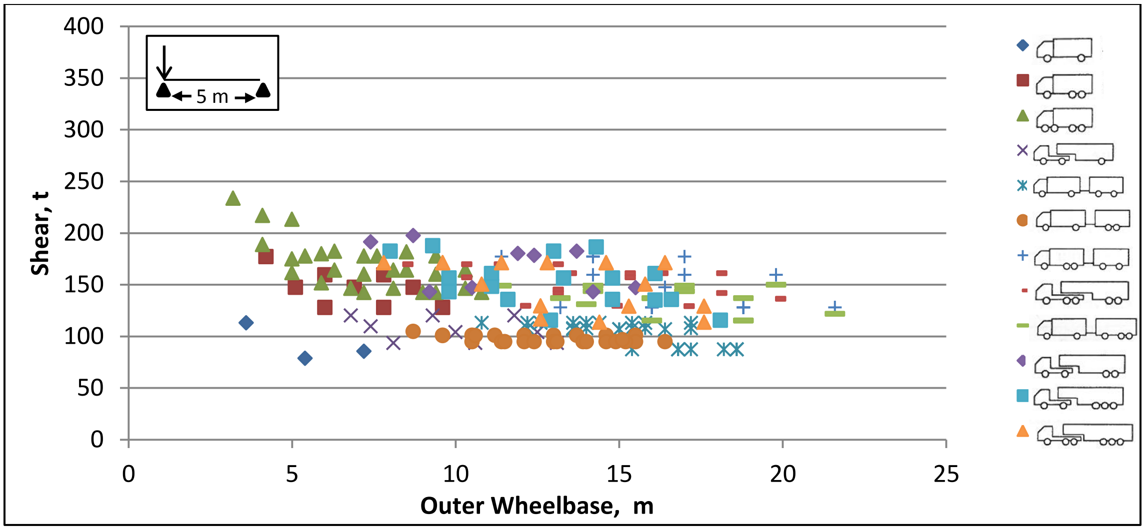


Figure 33: Shear stresses over the support of a 5 metre single span bridge

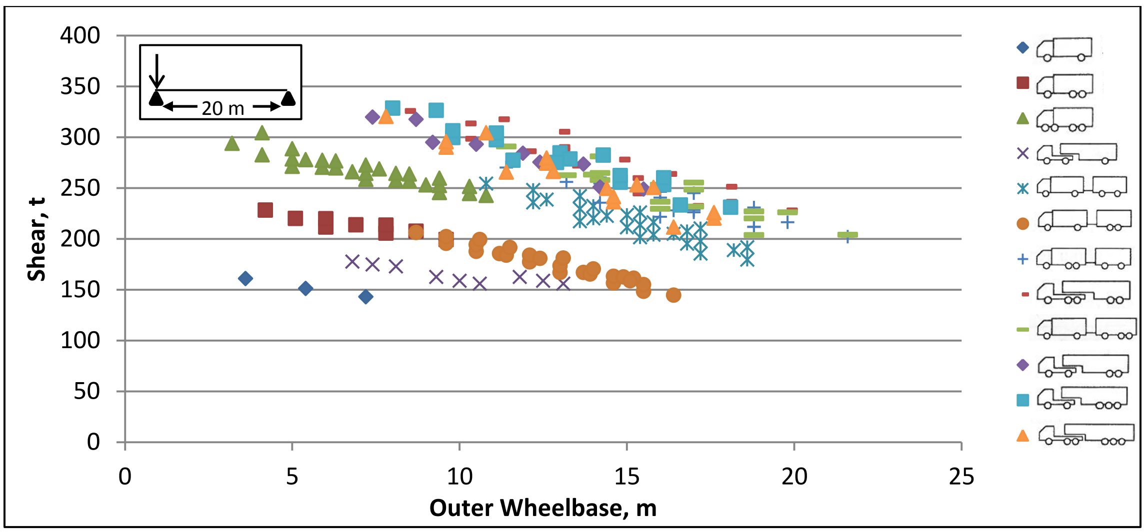


Figure 34: Shear stresses over the support of a 20 metre single span bridge

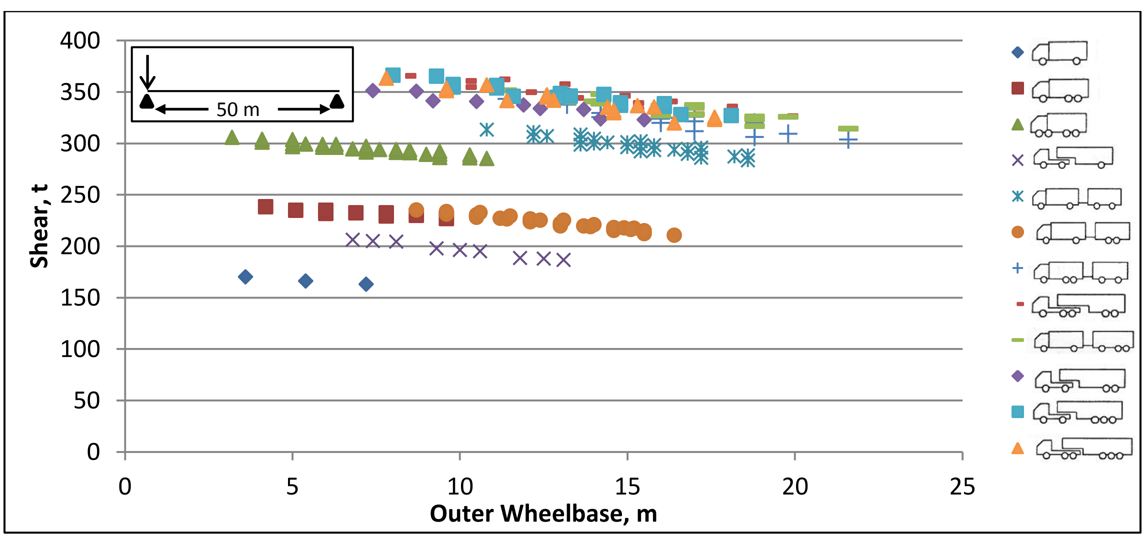


Figure 35: Shear stresses over the support of a 50 metre single span bridge

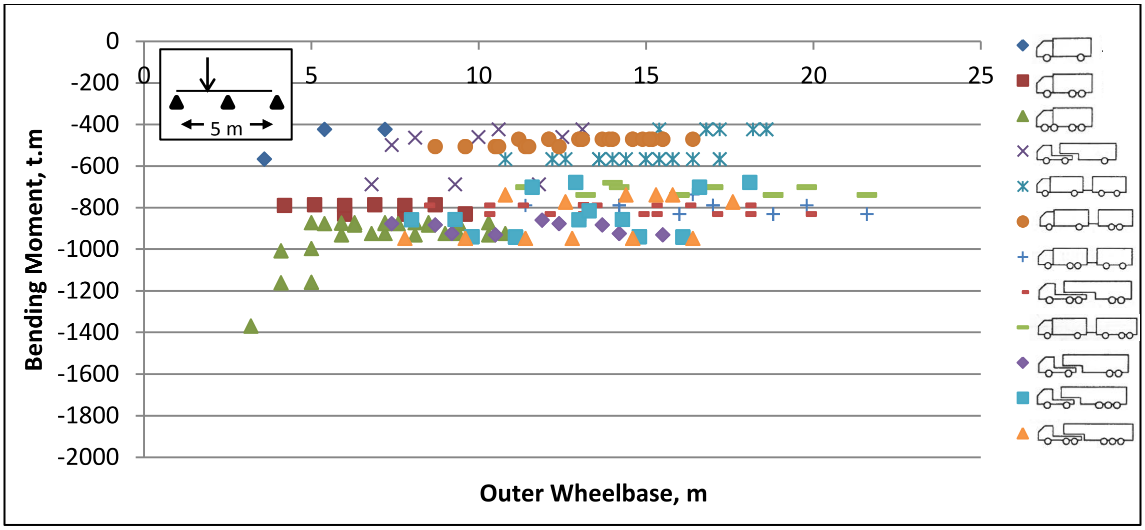


Figure 36: Bending moment stresses over the support of a 5 metre continuous span bridge

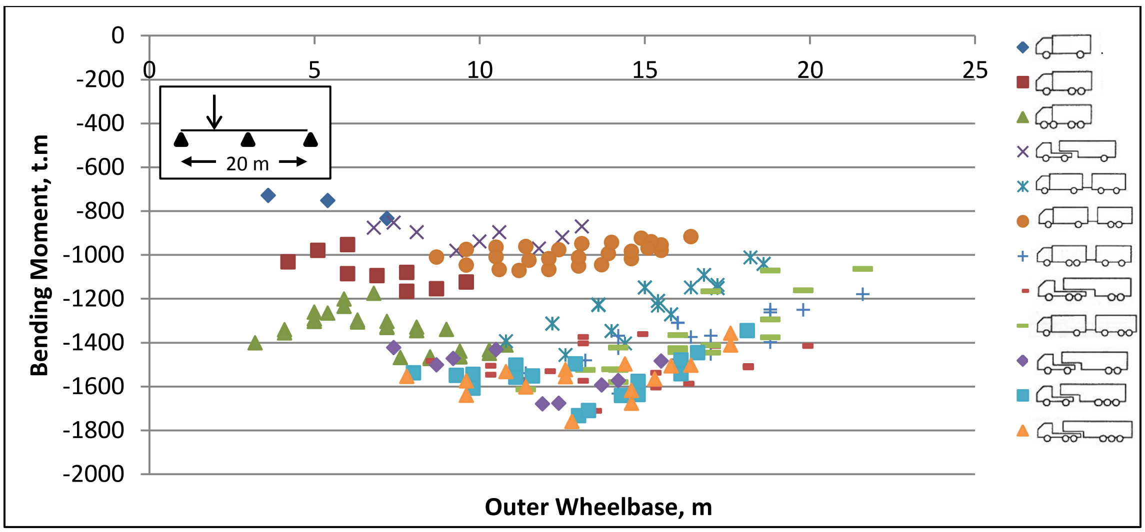


Figure 37: Bending moment stresses over the support of a 20 metre continuous span bridge

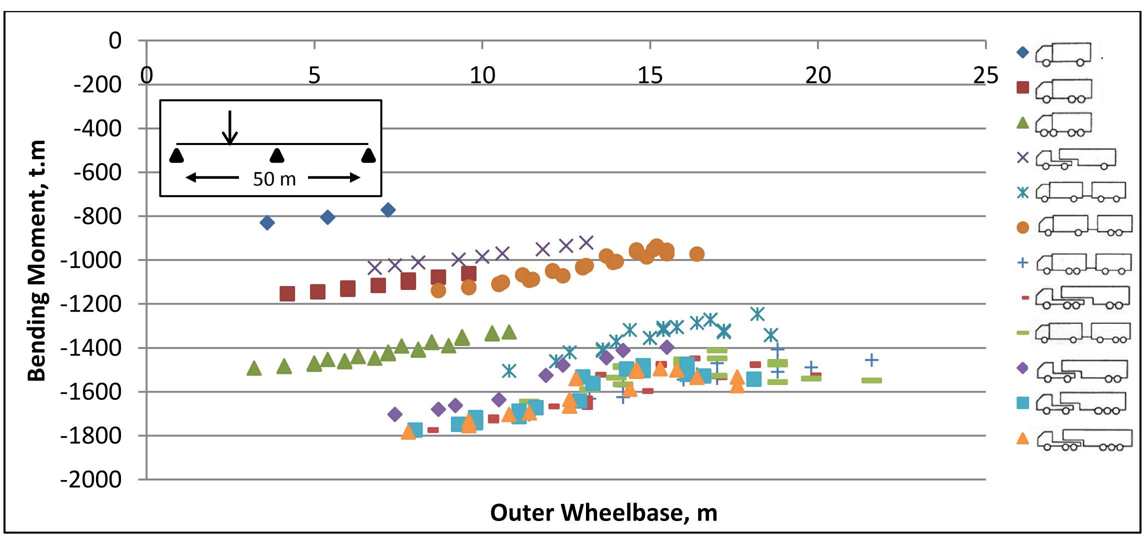


Figure 38: Bending moment stresses over the support of a 50 metre continuous span bridge

The impact of truck configurations can be noticed in the Figures when comparing the different truck configurations in terms of axle spacing, number of axles, allowable axle loads, and GVW (all shown in Appendix A). The 4-axle single unit truck imposes higher stresses relative to the other 2-axle and 3-axle single unit trucks even with longer wheelbases in most cases, with the highest stress imposed on 5 metre spans relative to all other truck configurations. The imposed stresses are also higher than the longer combination vehicles of 2-S1 and T2-2 on 20 and 50 metre spans due to the higher GVW and shorter wheelbase. Therefore, the impact of short single unit trucks with high loads may be of concern in developing a bridge formula, specifically for shorter span bridges. This can also be noticed with the 2-axle truck and 2-axle trailer vehicle combination (T2-2) (Trucks 5 and 6 in Table 7 and Appendix A) where higher stresses are imposed with the spread of the 2 trailer axles relative to a tandem axle due to the higher allowable loads on the spread tandem axles.

The Figures show that the higher weights allowed on higher number of axles, even with increase in the vehicle length up to the maximum length limits, can impose higher bridge load stresses. For example, the 5-axle tractor-semitrailer (3-S2) (Truck 11 in Table 7) imposes higher bending moment stresses at mid-span of a 50 metre single span bridge between 2,200 t.m and 3,600and t.m relative to the 3-axle tractor-semitrailer (2-S1) (Truck 4 in Table 7), even though the overall vehicle length can be up to 4.8 metres longer. Similar relationship exists for imposed shear stress on single span bridges and negative bending moment stresses on continuous span bridges. Therefore, including the number of axles as a parameter in the EUBF would seem contradictory to the purpose of the formula in reducing overstressing of bridges.

4.4.1.2. Reference Vehicles

The level of impact of different variables on imposed stresses from reference vehicles is evaluated to determine the independent variables to be included in the bridge formula. Reference vehicles are the vehicle configurations with all axle spacing limits at mid-range. Figure 39, Figure 40, and Figure 41 show the imposed bending moment stresses as a function of wheelbase, number of axles, and gross vehicle weight for 5, 20, and 50 metre single span bridges. Similar correlations are noticed between the independent variables and shear stresses over the support of a single span bridge and bending moment stresses at mid-span for continuous span bridges, shown in Figures 42 to 44 and 45 to 47 respectively. In all three conditions, it is noticed that increase in wheelbase, number of axles, and GVW result in increase of imposed stresses. However, the stresses imposed on a 5 metre span bridge show poor correlation with the analyzed variables. This is because axle groups with spacing of 5 metres or less can be on a 5 metre span bridge at once, resulting in a narrow range of imposed stresses. For example, the 3.6 metre and 15.4 metre evaluated truck configurations impose the same maximum bending moment stress at mid-span, shown in Figure 39, because the maximum stress is imposed by the same axle group on both vehicles that is on the span at once.

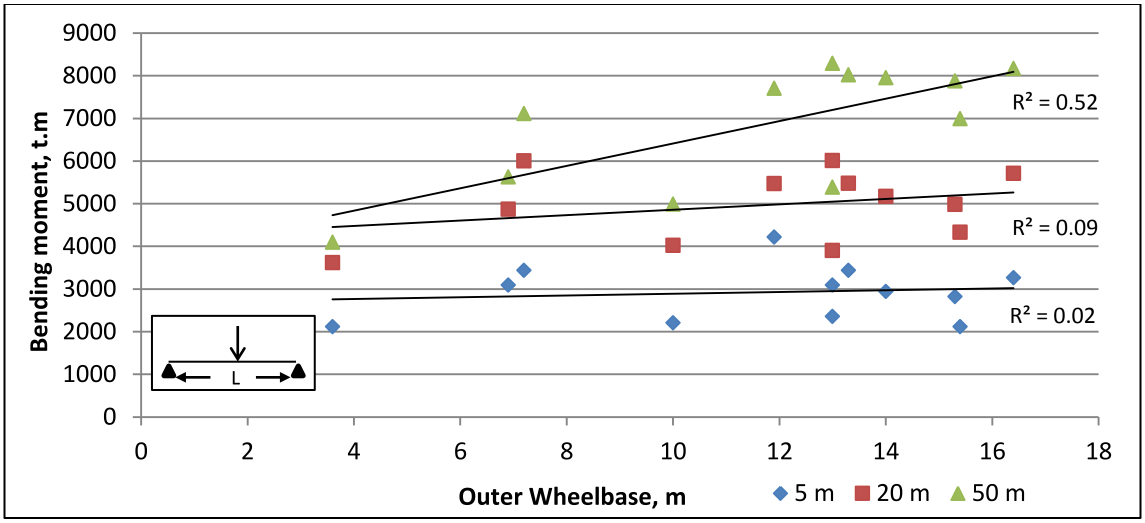


Figure 39: Imposed bending moment stresses as a function of reference vehicle's wheelbase on single span bridges at mid-span

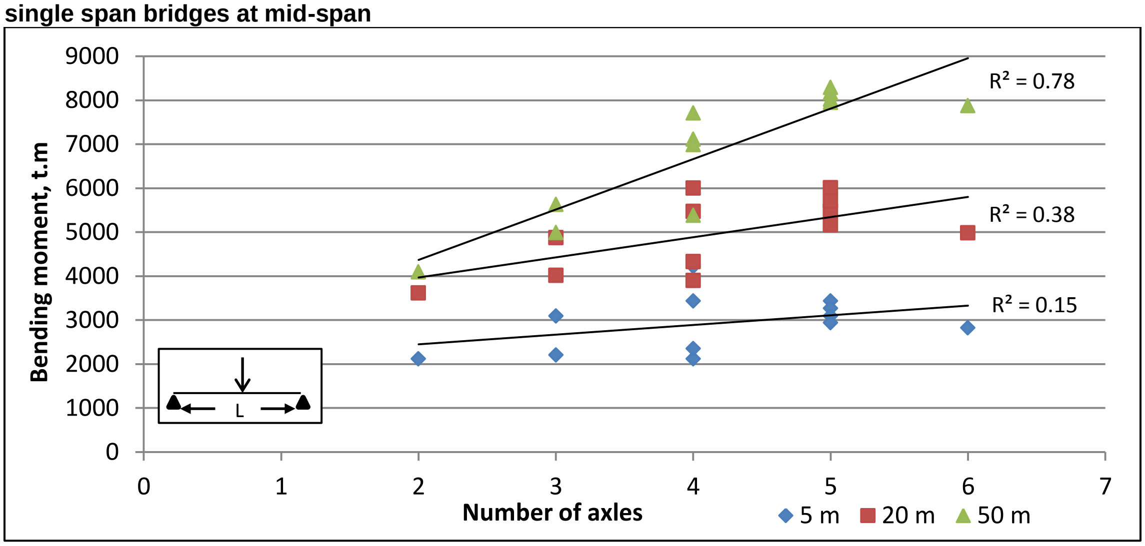


Figure 40: Imposed bending moment stresses as a function of number of axles of reference vehicles on single span bridges at mid-span

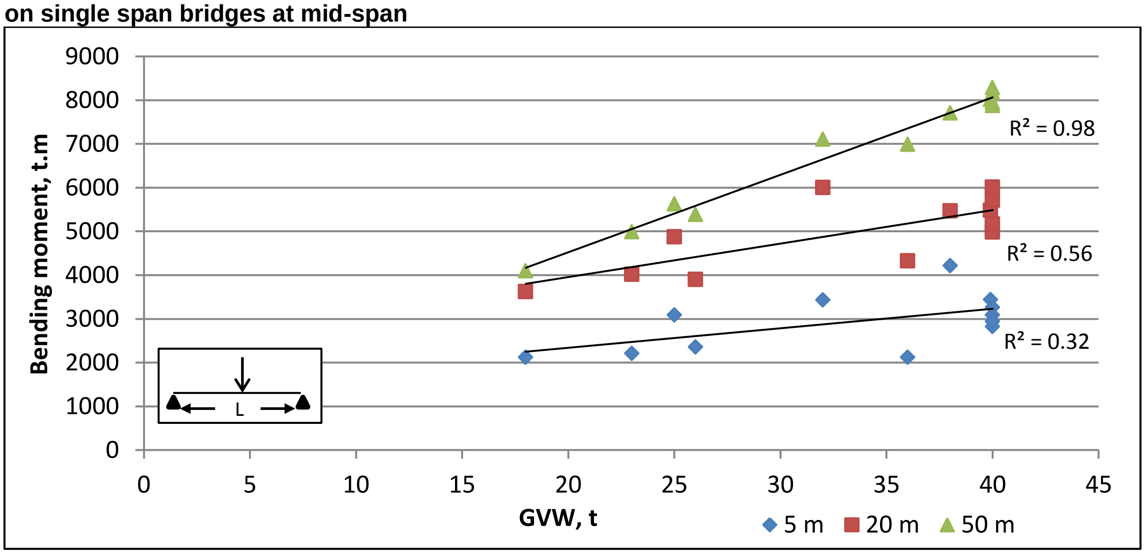


Figure 41: Imposed bending moment stresses as a function of gross vehicle weight of reference vehicles on single span bridges at mid-span

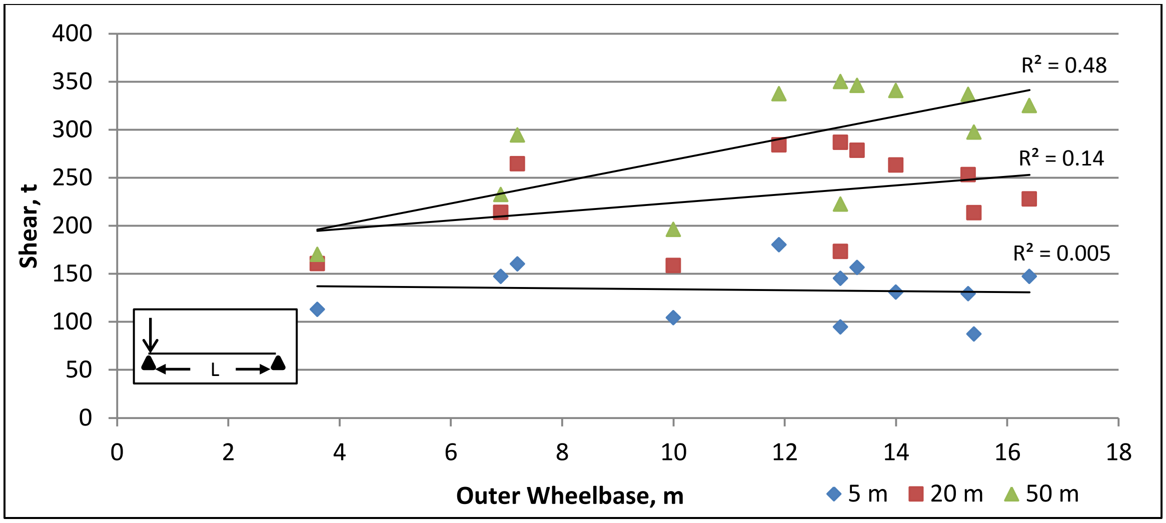


Figure 42: Imposed shear stresses as a function of wheelbase of reference vehicles over the support on single span bridges

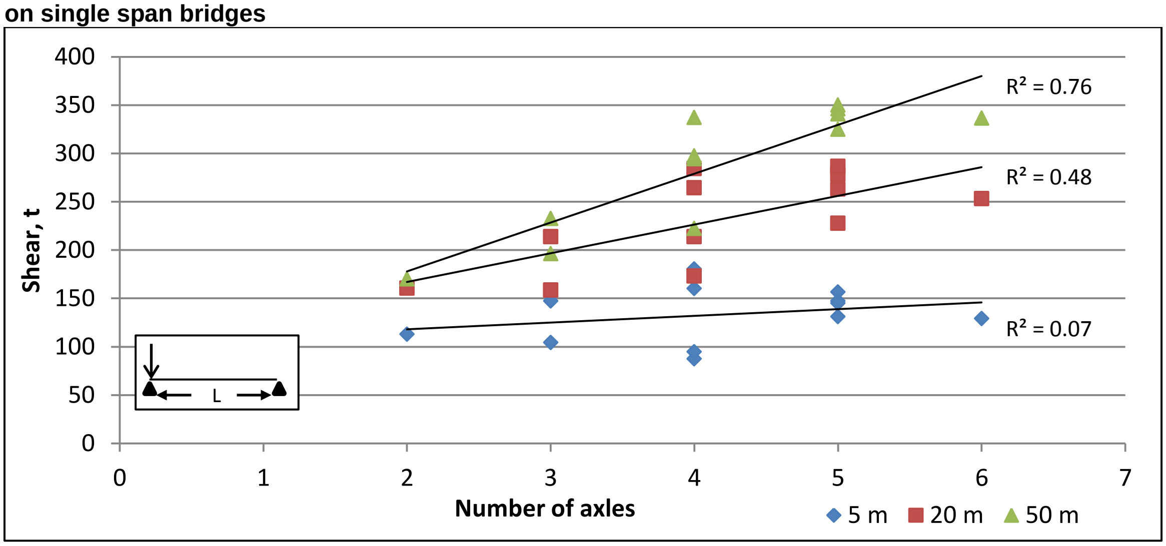


Figure 43: Imposed shear stresses as a function of number of axles of reference vehicles over the support on single span bridges

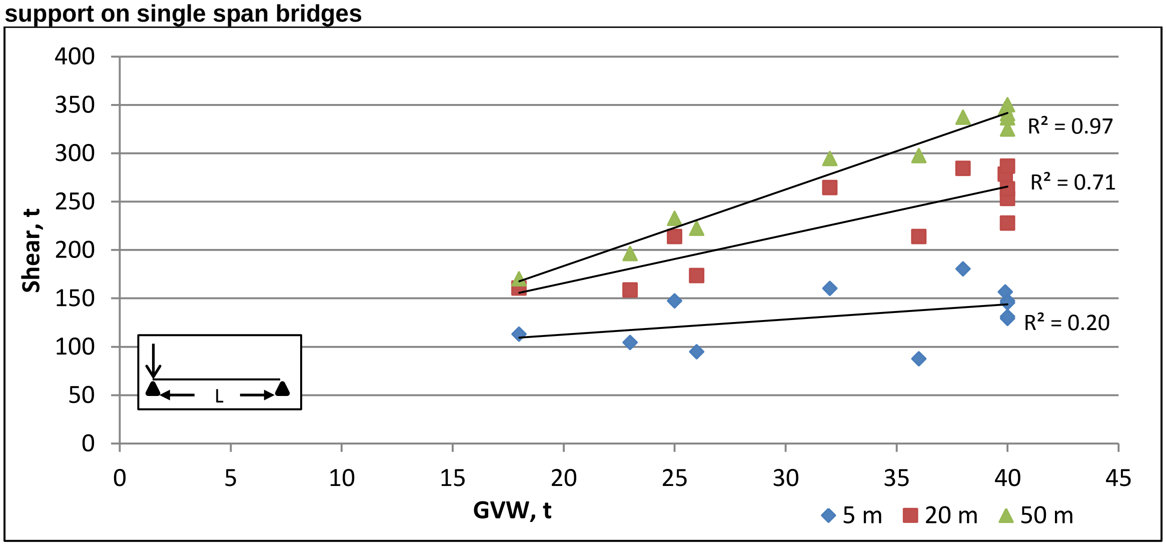


Figure 44: Imposed shear stresses as a function of gross vehicle weight of reference vehicles over the support on single span bridges

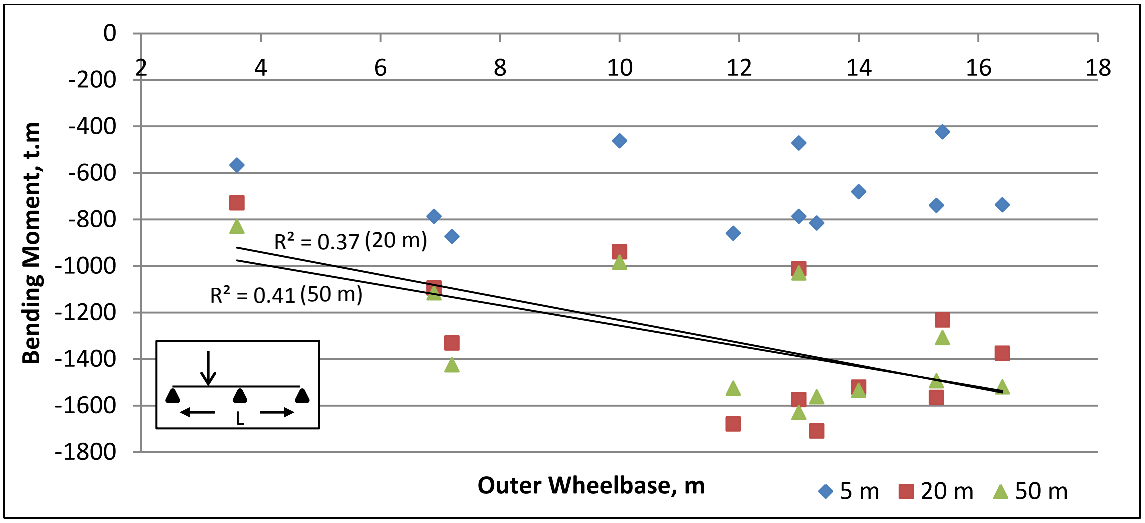


Figure 45: Imposed bending moment stresses as a function of wheelbase of reference vehicles over the support on continuous span bridges

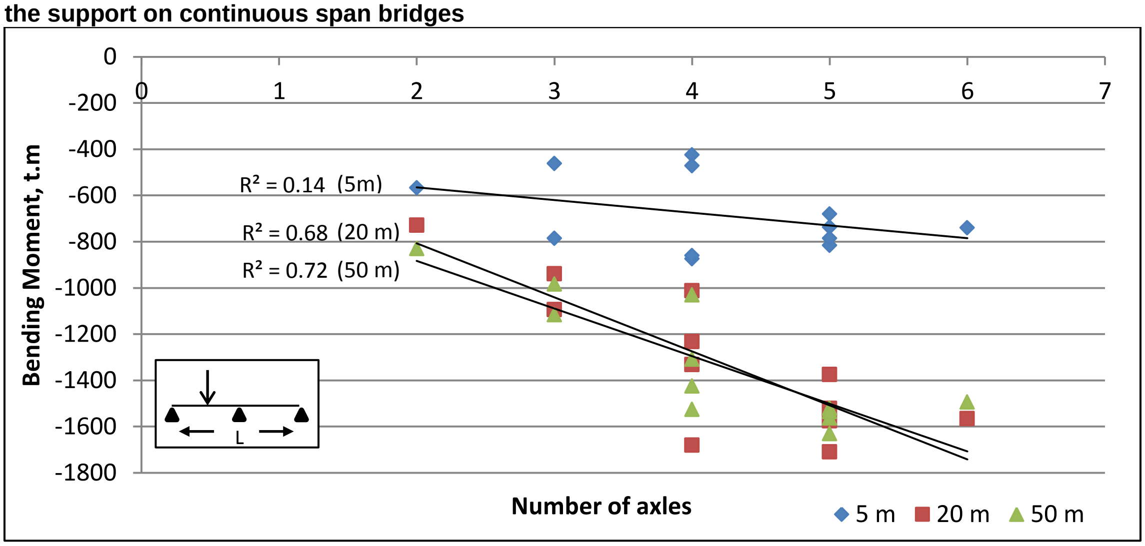


Figure 46: Imposed bending moment stresses as a function of number of axles of reference vehicles over the support on continuous span bridges

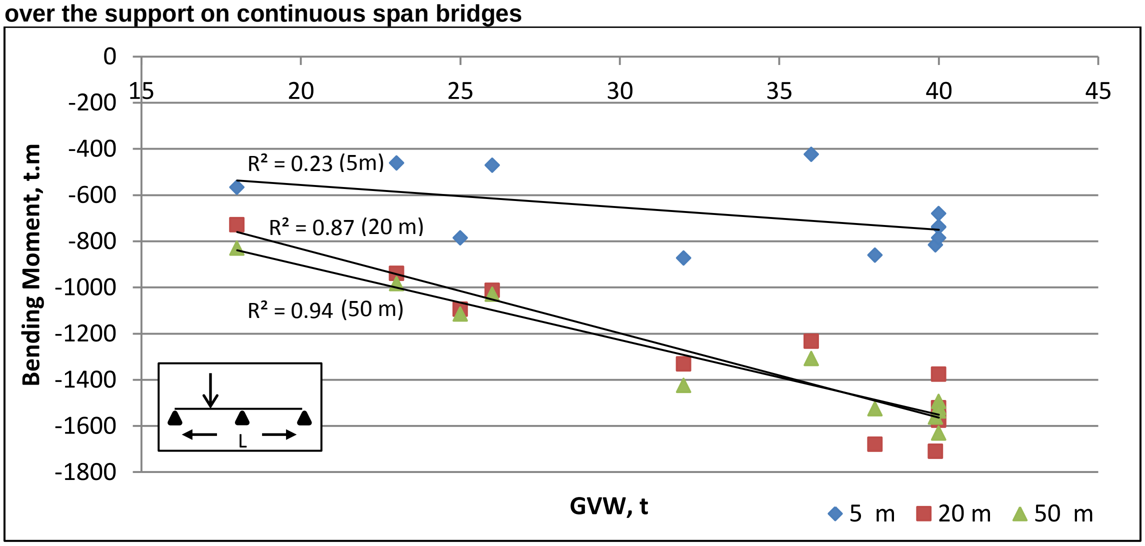


Figure 47: Imposed bending moment stresses as a function of gross vehicle weight of reference vehicles over the support on continuous span bridges

4.4.1.3. Stresses imposed by worst case and reference vehicles

For every truck configuration, the axle spacing combination that results in the highest imposed stresses was identified and referred to as the worst case vehicles (or worst case axle spacing combinations). The imposed load effects of the worst case and reference vehicles are shown in Figure 48, Figure 49, and Figure 50. This provides the basis for future work to identify the vehicle configurations and loadings that are acceptable for inclusion in a EUBF with the comparison of the imposed stresses to the Eurocode design stresses. The graphs show that the imposed load effects of the various truck configurations are within a consistent range, with no identifiable outliers. The maximum load effects in all three critical load cases are similar for the worst case and reference axle spacing combinations on 50 metre span bridges, while there is a greater difference between worst case and reference vehicle load effects on 20 metre span bridges. This is because the truck lengths are close to the 20 metre span length, therefore the axle spacing and axle loads impact the load effects. However, for spans longer than the overall length of a truck (e.g. 50 metre span), the gross weight and length of the truck are important (U.S. DOT, 2000). Therefore, for longer span bridges varying the internal axle spacings would not have a significant impact on the imposed load effects, rather the overall length of the vehicle would be the impacting factor.

The imposed load effects are in the range of 2,119 t.m to 8,845 t.m for bending moment stresses at mid-span of a single span bridge, 87 tonnes to 366 tonnes for shear stresses over the support of a single span bridge, and 424 t.m to 1,785 t.m for negative bending moment stresses over the support (pier) of a continuous span bridge.

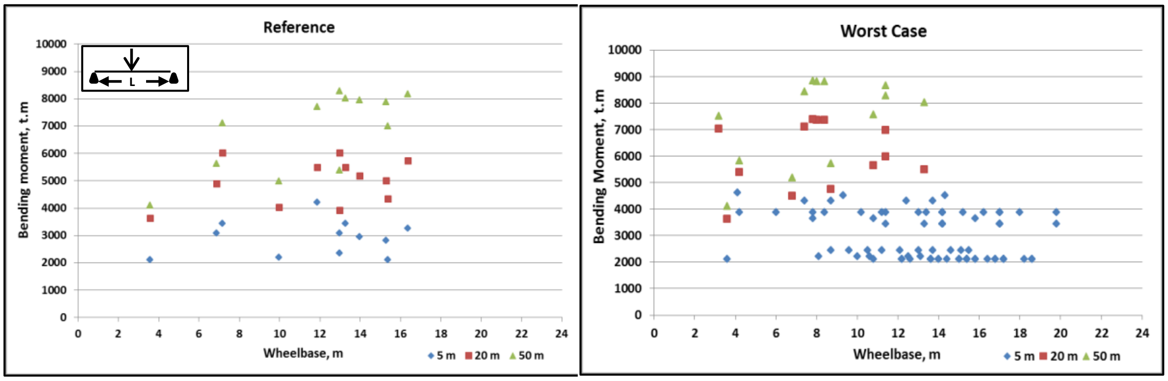


Figure 48: Bending moment stresses imposed on single span bridges at mid-span by worst case and reference vehicles

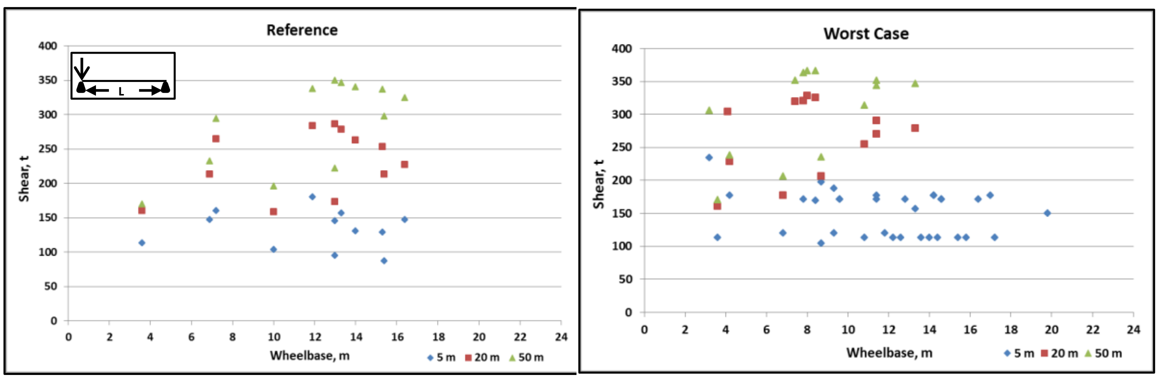


Figure 49: Shear stresses imposed on single span bridge over the support by worst case and reference vehicles

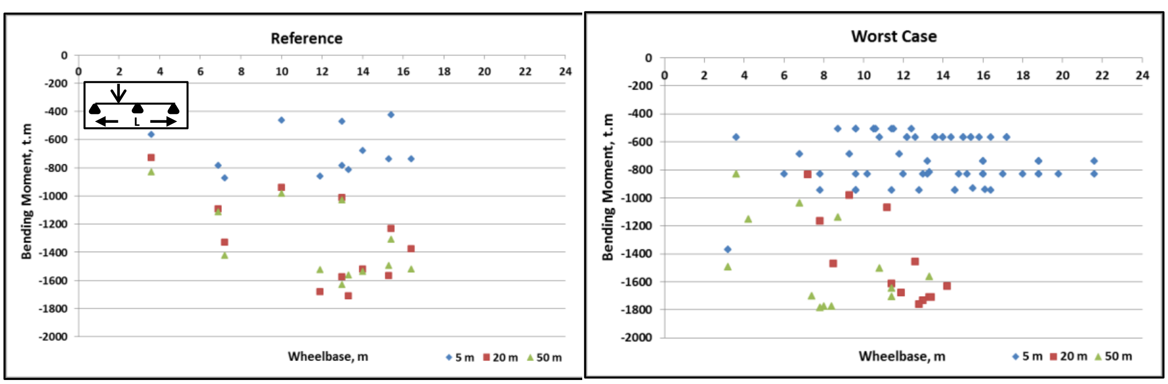


Figure 50: Bending moment stresses imposed on continuous span bridges over the support by worst case and reference vehicles

The aggressiveness ratio of the varying vehicle configurations is determined relative to the standard European five-axle truck with 16.5 metres in length and 40 tonnes GVW. The aggressiveness ratio of the vehicles is shown in Figure 51, Figure 52, and Figure 53. The level of aggressiveness of the vehicles can be compared to identify trucks (i.e., axle spacing combinations) that impose significantly high stress levels on bridges relative to the European reference truck. This can help identify vehicles that are deemed acceptable in terms of relative imposed load effects to include in the development of a bridge formula. Axle spacing combinations with significantly high imposed load effects relative to the practical European reference truck may not be suitable to operate regularly on bridges designed to support regular truck traffic.

The aggressiveness ratios vary between 0.43 and 1.35 for all three conditions of imposed stresses, except for the outliers of 1.49 aggressiveness ratio in terms of shear stress imposed over the support on single span bridges and 1.68 aggressiveness ratio in terms of negative bending moment stresses imposed over the support on two span continuous bridges, shown respectively in Figure 52 and Figure 53. These two aggressiveness ratios are caused by the four-axle single unit truck configuration (Truck 3 configuration in Table 7) with the minimum axle spacing limit. This vehicle is a single unit truck with two tandem axle groups spaced 2.3 metres apart. The worst case and reference vehicle configurations, other than the two outliers, can provide the live load envelope used for the development of a preliminary bridge formula relationship.

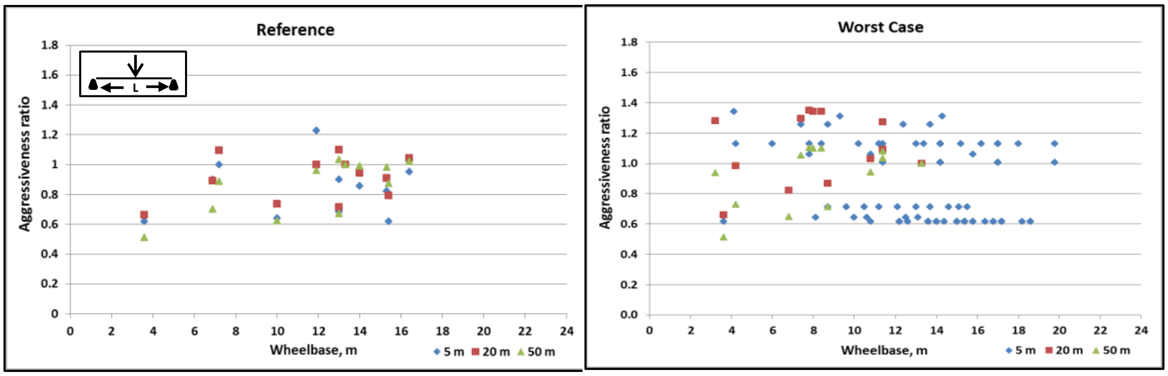


Figure 51: Aggressiveness ratio of reference and worst case trucks in terms of imposed bending moment stress at mid-span on single span bridges

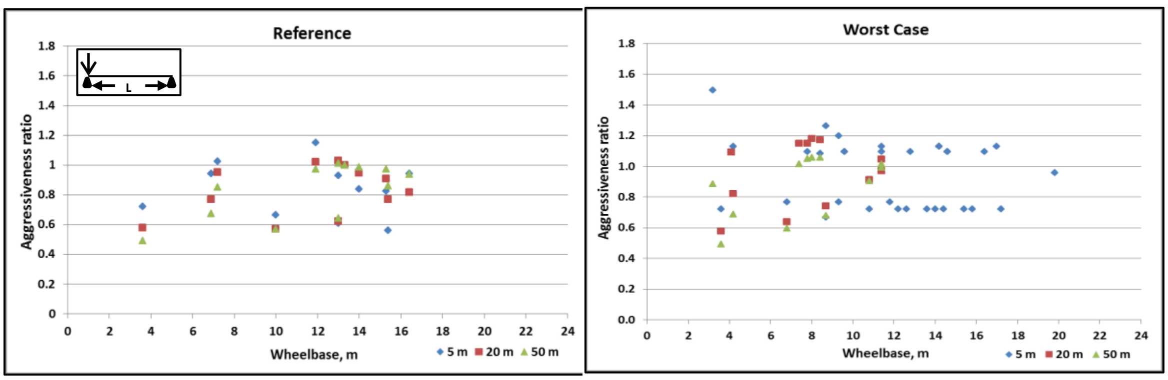


Figure 52: Aggressiveness ratio of reference and worst case trucks in terms of imposed shear stress over the support on single span bridges

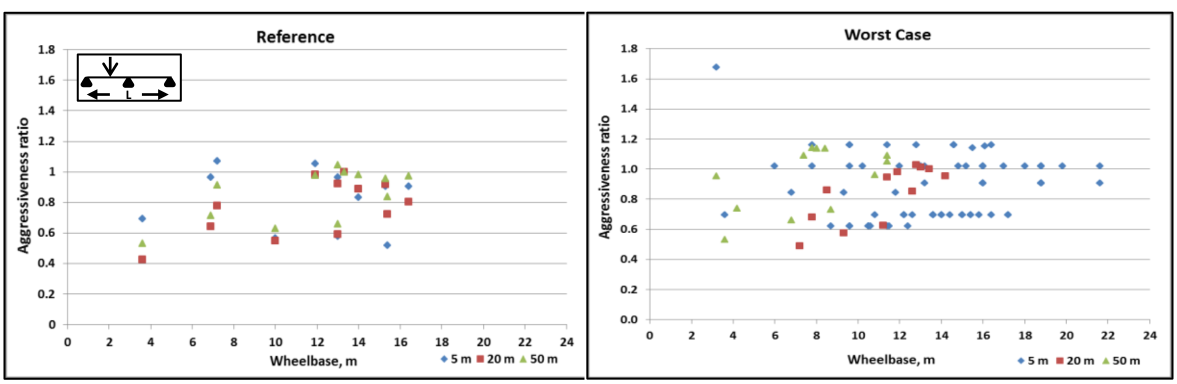


Figure 53: Aggressiveness ratio of reference and worst case trucks in terms of imposed bending moment stress over the support on continuous two span bridges

4.4.2. Observations from Analysis of European Truck Size and Weight Data

Observations from the analysis of truck size and weight data for the development of a European bridge formula are:

- Imposed stresses increase with increasing span length due to the increasing distance between bridge supports.
- Imposed stresses decline with increasing inter-axle spacing for a given vehicle on 20 and 50 metre span bridges. This is based on the concept of reducing imposed stresses by distributing the load over a longer distance. The imposed stresses on the short 5 metre span bridge does not vary significantly between different truck configurations as well as different inter-axle spacings for each truck configuration. This is because the entire length of most vehicles, except for the short single unit vehicles, are not on the bridge span at once due to lengths of greater than 5 metres; therefore axle groups govern the loading on the bridge.
- Short single unit trucks with high loads impose the highest stresses on 5 metre spans. The 4-axle single unit truck imposes the highest bending moment stresses on the 5 metre single span bridge relative to the other 2-axle and 3-axle single unit vehicles and most other combination vehicles. This truck configuration also imposes the highest shear stress over the support on a 5 metre single span bridge and bending moment over the pier on 5 metre two-span continuous span bridge relative to all other analyzed trucks. This is because the short wheelbase of the vehicle allows both tandem axles to be on the bridge span at once. Therefore, the impact of short single unit trucks with high loads may be of concern in terms of imposed stresses, specifically for shorter span bridges.
- The slope of the imposed load effects is lower for 50 metre and 5 metre span bridges than for 20 metre span bridges for a given vehicle as inter-axle spacing increases.

Truck configurations can be either shorter or longer than a 20 metre span bridge depending on the inter-axle spacing combination therefore the imposed stresses can vary more significantly on a 20 metre span bridge than on long (e.g. 50 metres) or short (e.g. 5 metre) span bridges where either the entire vehicle or only axle groups can be on the span at once, respectively.

- Increasing number of axles can impose higher bridge stresses. Higher weights allowed on vehicles with higher number of axles, even with increase in the vehicle length up to the maximum length limits, can impose higher bridge load stresses.

4.4.3. Considerations for a European Bridge Formula

In the development of a European bridge formula, it is necessary that the resulting equation have the following characteristics:

- Have a simple form to understand and use. Bridge formulae should be easily understood and applied by carriers and truck enforcement staff to regulate truck weights at truck inspection stations.
- Be applied to both internal and external axle spacings (inner and outer bridge) to ensure adequate load distribution on both internal and external axle groups.
- Consider axle group spacing and possibly number of axles in every axle group as parameters in determining the allowable load on axle groups with the bridge formula.
- Compatible to the jurisdiction's infrastructure and truck fleet characteristics. The bridge formula should limit imposed critical bending moment and shear stresses on single and continuous span bridges of varying lengths in accordance to design live loads specified in the Eurocode. Single and continuous spans respond differently to loadings, therefore the imposed stresses on both bridge types must be considered. In addition, shorter span lengths are impacted by internal axle group spacing and loading while longer spans are impacted by overall length and GVW of vehicles.

- Conform to European truck sizes and weights specified by the European Directive 96/53/EC. The European Directive truck configurations and their imposed bridge load stresses analyzed in this research can form the basis for the development of a EUBF. These stresses must be compared to the Eurocode design load stresses to ensure they do not exceed the design stresses by a certain overstress criteria. The overstress criteria should be selected suitable to Europe's bridge design loads and truck fleet while considering the structural integrity and expected life-span of bridges. In principle, higher overstressing of bridges relative to their design loads and higher frequency of heavy vehicle crossings may reduce the design-life of bridges.
- An additional bridge formula may be developed conforming to longer and heavier vehicles with the introduction of European Modular System vehicles in northern Europe. This is similar to other countries (Australia, South Africa, and Mexico) where a set of bridge formula with varying levels of restrictiveness are used to limit truck size and weight based on vehicle and route classification.
- Take into account the effects of possible side by side loading of trucks and the cumulative effect of a platoon of heavy vehicles.
- Consider the effect of fatigue in the development of the bridge formula to ensure that the serviceability of bridges are within acceptable limits.

For an initial step the preliminary bridge formula could follow the format of the most common international bridge formulae. The candidate formula formats are:

1. $W = aL + b$
2. $W = aL + bN + c$
3. $W = a * (\frac{LN}{N-1}) + bN + c$

Where:

W= allowable weight on the axle group

L= axle group spacing (which could be applied to the vehicle length or every axle combination)

N= number of axles

a, b, c = constant values

The first bridge formula format ($W = aL + b$) can be applied to both overall vehicle length and GVW (12 vehicle configurations) or internal axle spacings and axle group loads (192 axle spacing combinations when not incorporating the 4-axle single unit truck with its shortest axle spacing combination resulting in high aggressiveness ratios). Figure 54 shows the relationships between the overall length and allowable GVW of the evaluated European Directive trucks, where L is the vehicle's outer wheelbase (outer bridge). Figure 55 shows the relationships between the spacing of every axle group combination (inner and outer bridge) and the allowable weight on the axle group, where L is the axle spacing between every axle group combination. It is noticed from this Figure that the number of axles has a significant impact on the allowable axle group weights based on European truck size and weight regulations. Bridge formula formats 2 and 3 include the number of axles as a parameter in determining the allowable weights on axle groups. Bridge formula format 3 follows the U.S. Bridge Formula B format. These formulae may be suitable to the European truck sizes and weights, since the number of axles in axle groups seems to have an impact on the allowable weights in Figure 55.

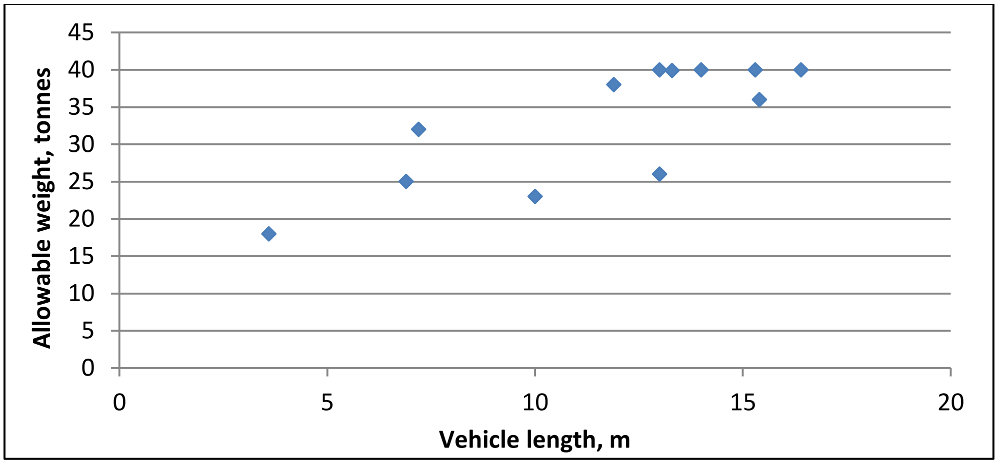


Figure 54: Allowable gross vehicle weights as a function of total vehicle length for a series of EU Directive vehicles

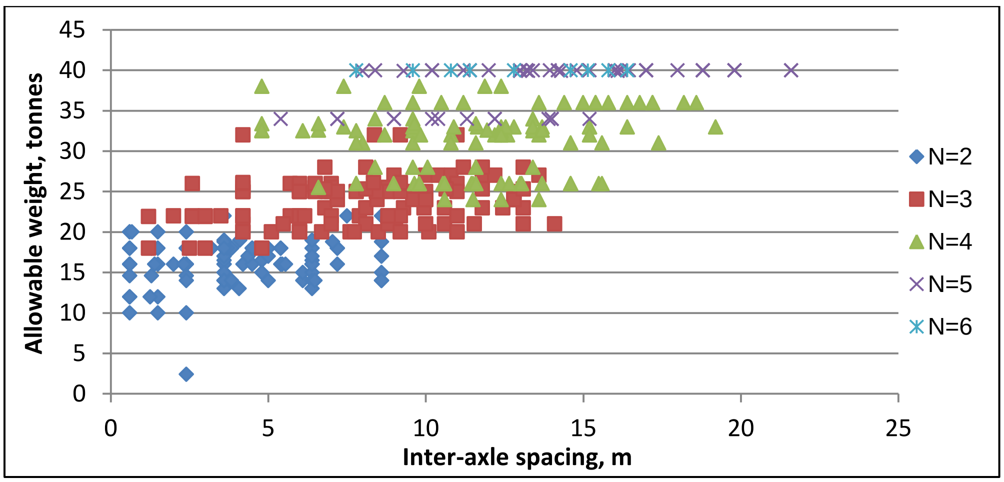


Figure 55: Allowable axle group weights as a function of axle group spacing for a series of EU Directive vehicles
N= number of axles in group

However, the bridge load analysis in this research shows that the higher weights allowed on higher number of axles, even with increase in the vehicle length up to the maximum length limits, impose higher bridge load stresses. The impact of number of axles on imposed stresses are shown in the analysis conducted in Section 4.4.1.2, where higher stresses are imposed, particularly on longer spans, with increasing number of vehicle axles. Therefore, including the number of axles as a parameter in the EUBF would seem contradictory to the purpose of the formula in reducing overstressing of bridges. This is similar to criticisms of the U.S. BFB which in some cases the number of axles on heavy vehicles were increased to take advantage of the BFB allowable weights without the adequate vehicle length increase, resulting in overstressing of bridges above the overstress criteria. These vehicles can also cause issues with safety and dynamic performance of vehicles. On the other hand, the number of axles may positively impact pavements, therefore, the formula must be checked for effects on pavements.

5. CONCLUSION AND RECOMMENDATIONS

This Chapter provides conclusions and recommendations for future research in this field.

Bridge Design Methods

Bridge design loads and methods have evolved over the years with increased understanding of structural behaviour and loading. In principle, higher capacity bridges should be allowed or permitted to support higher operating loads.

Load models are applied differently in terms of superimposing lane loads, dynamic load allowances, and load factors used in the Load and Resistance Factor Design (LRFD). For example Canadian bridges designed to both CSA and OHBDC bridge design codes are designed to allow significantly higher live-loads than the U.S. bridges of up to double that for HS20 loads for 45 metre simple span bridges (with the exception of short span bridges up to 15 metres).

Bridge design methods and loads may vary significantly amongst countries and regions, which impact the truck size and weight regulations within the jurisdiction. Increased efforts are being placed to achieve an appropriate balance between truck productivity and infrastructure design, operation, and maintenance to allow increased utilization of the bridge capacities while ensuring reasonable service life of roadway systems.

International Bridge Formulae

Bridge formulae can be a useful method to regulate truck size and weight limits while ensuring the structural capacity of bridges by limiting the imposed overstress on bridges. The level of efficiency of bridge formulae can vary depending on the design criteria used in the development of the formula, the compatibility to the jurisdiction’s infrastructure and truck fleet characteristics, and the method of implementation as part of the regulation and by operators in the trucking industry.

Many issues may arise from the implementation of an unsuitable bridge formula for the infrastructure and transportation characteristics of a jurisdiction in terms of the design overstress criteria and additional axle spacing and weight limits. For example, the U.S. Bridge Formula B is criticized for being overly restrictive for short specialized hauling vehicles (SHV), therefore resulting in the introduction of long draw bars on SHVs. The unintended, and possibly undesirable, outcomes of implementation of a bridge formula or any change in truck size and weight regulations must be monitored and resolved for safety, dynamic performance and infrastructure impacts. In addition, due to the wide range of truck configurations and bridge strength capacities, it is difficult to develop one bridge formula suitable to adequately regulate weights on all truck configurations for all bridge types. The Mexican and Australian bridge formulae allow different weights on different route classifications with suitable strength capacities.

With the continuously changing infrastructure and truck transportation characteristics, bridge formulae must be re-evaluated and updated to ensure the adequacy to limit weights.

Bridge Load Analysis

The analysis conducted in this research consists of two components: (1) comparison of international bridge formula and (2) load effect of European Directive trucks.

Comparison of International Bridge Formulae

The varying levels of restrictiveness of existing bridge formulae applied in different countries can be noticed through the comparison of the allowable weights and imposed load effects on bridges, while keeping in mind the differences in infrastructure capacity and truck fleet characteristics of each jurisdiction. The bridge formulae imposed the highest bending moments when the highest gross vehicle weights were allowed.

When applying the bridge formulae to the outer bridge of vehicles, the Australian bridge formula used for limiting weights on general access vehicles and road trains on Category 1 routes is the most permissive, followed by the South African bridge formula. In accordance, these bridge formulae impose the highest bridge load effects, in terms of bending moment at mid-span. For the analyzed truck configurations, the BFB and Mexican bridge formula allow the lowest gross vehicle weights up to the truck configuration with 18.2 metre wheelbase, when the New Zealand bridge formula becomes the most restrictive after this outer wheelbase distance due to the 44 tonne limit.

Existing bridge formulae, except for the Mexican bridge formula, must also be applied to all internal axle combinations which may result in lower allowable GVW for some truck configurations. Allowing GVWs determined by applying only the outer bridge formulae may result in axle loads that exceed the overstress criteria used in the development of these bridge formulae.

In addition to the restrictiveness of bridge formulae themselves, the truck configurations can have an impact on the amount of imposed bridge load stresses. For example, the imposed load effect of the European reference truck configuration (2-S3) is generally higher relative to the Canadian and U.S. reference truck configurations (3-S2) for all bridge formula allowable weights, except for the Mexican bridge formula. This is because the tridem axle on the European vehicle is allowed to carry higher weights relative to the tandem axle on the Canadian and U.S. vehicles, which imposes higher stresses.

Load Effect of European Directive Trucks

The analysis of the European truck size and weight regulations and the imposed load effects on bridges is conducted with a view to identifying issues and providing the basis for developing a European bridge formula.

In developing a bridge formula, the imposed bending moment and shear stresses on different bridge types of varying span lengths should be considered. Both single and continuous spans should be considered due to their different behavioural characteristics in response to loading. For example, in the case of continuous spans, the critical load effect is over the pier due to negative bending moment stresses whereas on single spans it is at mid-span with positive bending moment stresses. Shorter span lengths (e.g. 5 metre span) determine the internal distribution of loads and the imposed stresses by axle groups, for example tandem and tridem axles. For spans longer than the overall length of a truck (e.g. 50 metre span), the gross vehicle weight and overall length of the truck will be the impacting factor.

The analyzed European Directive trucks show declining imposed stresses with increased vehicle lengths for constant weights on 20 and 50 metre span bridges, while increasing GVWs result in increased imposed stresses. The impact of short single unit trucks with high loads may be of concern in developing a bridge formula, particularly for short spans. The 4-axle single unit truck imposes higher stresses relative to the other 2-axle and 3-axle single unit trucks, while imposing the highest stresses on 5 metre spans relative to all other truck configurations and resulting in the highest aggressiveness ratio.

The bridge load analysis shows that the higher weights allowed on higher number of axles, even with increase in the vehicle length up to the maximum length limits, can impose higher bridge load stresses. For example, the 5-axle tractor-semitrailer (Truck 11, 3-S2 in Table 7) imposes higher bending moment stresses at mid-span of a 50 metre single span bridge by a minimum 2,200 t.m relative to the 3-axle tractor-semitrailer (Truck 4), even when considering the shortest wheelbase for Truck 4 (resulting in the highest stresses) and the longest wheelbase for Truck 11 (resulting in the lowest stresses). A similar relationship exists for imposed shear stress on single span bridges and negative bending moment stresses on continuous span bridges. Therefore, including the number of axles as a parameter in the EUBF would seem contradictory to the purpose of the formula in reducing overstressing of bridges. On the other hand, the number of axles may positively impact pavement performance; therefore, the formula must be checked for effects on pavements.

A EU bridge formula would allow for future truck size and weight evolutions over a long-term period, while preserving the existing stock of bridges, designed with past and current loading codes. The bridge formula would be applied in addition to the European Directive prescriptive regulations, conforming to European truck and infrastructure characteristics. The formula could be used as an initial check for trucks larger and heavier than the EU directive vehicles or for increase in truck size and weight regulations to ensure the protection of bridges against damaging overstress.

Continuing Research Needs

Further analysis must be conducted on the development of a EUBF to evaluate the formula format best suited to fit the truck size and weight data, while considering additional factors to overstressing of bridges including fatigue effects, effect on pavements, presence of multiple vehicles (i.e. platoon of vehicles) and multiple lane loadings. Real dynamic truck weights and imposed bridge stresses measured from roadway and bridge Weigh-in-Motion sensors would be useful in calibrating the bridge formula.

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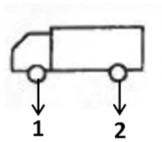
7. APPENDIX A

European Directive Truck Configurations and Axle Spacing Combinations

APPENDIX A: European Directive Truck Configurations and Axle Spacing Combinations

Appendix A shows the 12 European Directive truck configurations, their axle weights, and the varying axle spacing combinations used in the analysis of European truck size and weight data for the development of a European Bridge Formula. The axle spacings range from maximum, mid-range, and minimum spacing limits, resulting in a total of 193 axle spacing combinations.

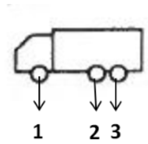
Truck 1: Two axle single unit truck



Axle No	Axle Load (tonnes)
1	9
2	9

Axle Spacing (metres)
Axle 1 to 2
3.6
5.4
7.2

Truck 2: Three axle single unit truck

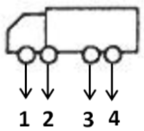


Axle No	Axle Load (tonnes)
1	7
2	9
3	9

Axle Spacing combinations (metres)	
Axle 1 to 2	**Axle 2 to 3**
3.6	0.6
3.6	1.5
3.6	2.4
5.4	0.6
5.4	**1.5**
5.4	2.4
7.2	0.6
7.2	1.5
7.2	2.4

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.

Truck 3: Four axle single unit truck

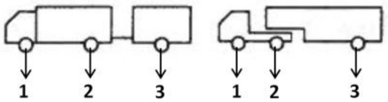


Axle No	Axle Load (tonnes)
1	6
2	6
3	10
4	10

Axle Spacing combinations (metres)		
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**
0.6	2	0.6
0.6	2	1.5
0.6	2	2.4
0.6	4.2	0.6
0.6	4.2	1.5
0.6	4.2	2.4
0.6	6.4	0.6
0.6	6.4	1.5
0.6	6.4	2.4
1.5	2	0.6
1.5	2	1.5
1.5	2	2.4
1.5	4.2	0.6
1.5	**4.2**	**1.5**
1.5	4.2	2.4
1.5	6.4	0.6
1.5	6.4	1.5
1.5	6.4	2.4
2.4	2	0.6
2.4	2	1.5
2.4	2	2.4
2.4	4.2	0.6
2.4	4.2	1.5
2.4	4.2	2.4
2.4	6.4	0.6
2.4	6.4	1.5
2.4	6.4	2.4

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold

Truck 4: Three axle truck and one axle trailer or three axle tractor-semitrailer

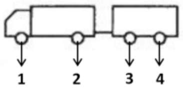


Axle No	Axle Load (tonnes)
1	9
2	9
3	5

Axle Spacing combinations (metres)	
Axle 1 to 2	**Axle 2 to 3**
3.2	3.6
3.2	6.1
3.2	8.6
3.85	3.6
3.85	**6.1**
3.85	8.6
4.5	3.6
4.5	6.1
4.5	8.6

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold

Truck 5: two axle truck and two axle trailer

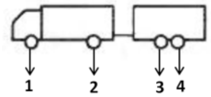


Axle No	Axle Load (tonnes)
1	9
2	9
3	9
4	9

Axle Spacing combinations (metres)		
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**
3.6	3.6	3.6
3.6	3.6	5.0
3.6	3.6	6.4
3.6	5.4	3.6
3.6	5.4	5.0
3.6	5.4	6.4
3.6	7.2	3.6
3.6	7.2	5.0
3.6	7.2	6.4
5.0	3.6	3.6
5.0	3.6	5.0
5.0	3.6	6.4
5.0	5.4	3.6
5.0	**5.4**	**5.0**
5.0	5.4	6.4
5.0	7.2	3.6
5.0	7.2	5.0
5.0	7.2	6.4
6.4	3.6	3.6
6.4	3.6	5.0
6.4	3.6	6.4
6.4	3.6	3.6
6.4	3.6	5.0
6.4	3.6	6.4
6.4	5.4	3.6
6.4	5.4	5.0
6.4	5.4	6.4
6.4	7.2	3.6
6.4	7.2	5.0
6.4	7.2	6.4

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.

Truck 6: Two axle truck and tandem axle trailer

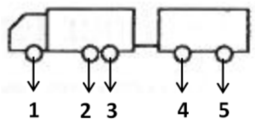


Axle No	Axle Load (tonnes)
1	6
2	10
3	5
4	5

Axle Spacing combinations (metres)		
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**
4.5	3.6	0.6
4.5	3.6	1.5
4.5	3.6	2.4
4.5	6.1	0.6
4.5	6.1	1.5
4.5	6.1	2.4
4.5	8.6	0.6
4.5	8.6	1.5
4.5	8.6	2.4
5.45	3.6	0.6
5.45	3.6	1.5
5.45	3.6	2.4
5.45	6.1	0.6
5.45	**6.1**	**1.5**
5.45	6.1	2.4
5.45	8.6	0.6
5.45	8.6	1.5
5.45	8.6	2.4
6.4	3.6	0.6
6.4	3.6	1.5
6.4	3.6	2.4
6.4	6.1	0.6
6.4	6.1	1.5
6.4	6.1	2.4
6.4	8.6	0.6
6.4	8.6	1.5
6.4	8.6	2.4

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.

Truck 7: Three axle truck and two axle trailer

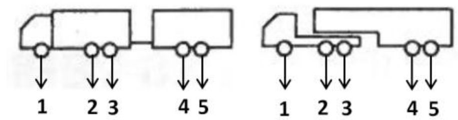


Axle No	Axle Load (tonnes)
1	7
2	9
3	9
4	7.5
5	7.5

Axle Spacing combinations (metres)			
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**	**Axle 4 to 5**
3.6	0.6	3.6	3.6
3.6	0.6	3.6	6.4
3.6	0.6	6.4	3.6
3.6	0.6	6.4	6.4
3.6	2.4	3.6	3.6
3.6	2.4	3.6	6.4
3.6	2.4	6.4	3.6
3.6	2.4	6.4	6.4
6.4	0.6	3.6	3.6
6.4	0.6	3.6	6.4
6.4	0.6	6.4	3.6
6.4	0.6	6.4	6.4
6.4	2.4	3.6	3.6
6.4	2.4	3.6	6.4
6.4	2.4	6.4	3.6
6.4	2.4	6.4	6.4
5.55	**1.3**	**4.8**	**4.8**

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.

Truck 8: three axle truck and tandem axle trailer or five axle tractor-semitrailer

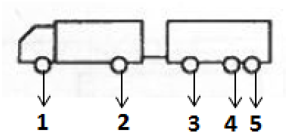


Axle No	Axle Load (tonnes)
1	6
2	8
3	8
4	9
5	9

Axle Spacing combinations (metres)			
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**	**Axle 4 to 5**
3.6	0.6	3.6	0.6
3.6	0.6	3.6	2.4
3.6	0.6	8.6	0.6
3.6	0.6	8.6	2.4
3.6	2.4	3.6	0.6
3.6	2.4	3.6	2.4
3.6	2.4	8.6	0.6
3.6	2.4	8.6	2.4
6.4	0.6	3.6	0.6
6.4	0.6	3.6	2.4
6.4	0.6	8.6	0.6
6.4	0.6	8.6	2.4
6.4	2.4	3.6	0.6
6.4	2.4	3.6	2.4
6.4	2.4	8.6	0.6
6.4	2.4	8.6	2.4
5.0	**1.5**	**5.0**	**1.5**

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.

Truck 9: Two axle truck and three axle trailer

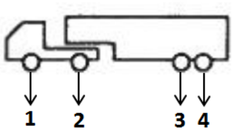


Axle No	Axle Load (tonnes)
1	7
2	12
3	5
4	8
5	8

Axle Spacing combinations (metres)			
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**	**Axle 4 to 5**
3.6	3.6	3.6	0.6
3.6	3.6	3.6	2.4
3.6	3.6	6.4	0.6
3.6	3.6	6.4	2.4
3.6	6.4	3.6	0.6
3.6	6.4	3.6	2.4
3.6	6.4	6.4	0.6
3.6	6.4	6.4	2.4
6.4	3.6	3.6	0.6
6.4	3.6	3.6	2.4
6.4	3.6	6.4	0.6
6.4	3.6	6.4	2.4
6.4	6.4	3.6	0.6
6.4	6.4	3.6	2.4
6.4	6.4	6.4	0.6
6.4	6.4	6.4	2.4
4.1	**4.4**	**4.1**	**1.4**

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.

Truck 10: Four axle tractor-semitrailer

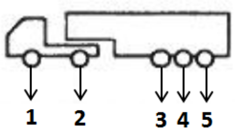


Axle No	Axle Load (tonnes)
1	6
2	12
3	10
4	10

Axle Spacing combinations (metres)		
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**
3.2	3.6	0.6
3.2	3.6	2.4
3.2	8.6	0.6
3.2	8.6	2.4
4.5	3.6	0.6
4.5	3.6	2.4
4.5	8.6	0.6
4.5	8.6	2.4
3.7	**7.5**	**0.68**

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.

Truck 11: Five axle tractor-semitrailer

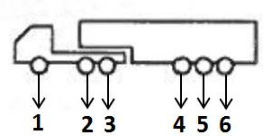


Axle No	Axle Load (tonnes)
1	6.5
2	11.5
3	7.3
4	7.3
5	7.3

Axle Spacing combinations (metres)			
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**	**Axle 4 to 5**
3.2	3.6	0.6	0.6
3.2	3.6	0.6	2.4
3.2	3.6	2.4	0.6
3.2	3.6	2.4	2.4
3.2	8.6	0.6	0.6
3.2	8.6	0.6	2.4
3.2	8.6	2.4	0.6
3.2	8.6	2.4	2.4
4.5	3.6	0.6	0.6
4.5	3.6	0.6	2.4
4.5	3.6	2.4	0.6
4.5	3.6	2.4	2.4
4.5	8.6	0.6	0.6
4.5	8.6	0.6	2.4
4.5	8.6	2.4	0.6
4.5	8.6	2.4	2.4
3.6	**7.1**	**1.3**	**1.3**

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.

Truck 12: Six axle tractor-semitrailer



Axle No	Axle Load (tonnes)
1	6
2	8
3	8
4	6
5	6
6	6

Axle Spacing combinations (metres)				
Axle 1 to 2	**Axle 2 to 3**	**Axle 3 to 4**	**Axle 4 to 5**	**Axle 5 to 6**
2.4	0.6	3.6	0.6	0.6
2.4	0.6	3.6	0.6	2.4
2.4	0.6	3.6	2.4	0.6
2.4	0.6	3.6	2.4	2.4
2.4	0.6	8.6	0.6	0.6
2.4	0.6	8.6	0.6	2.4
2.4	0.6	8.6	2.4	0.6
2.4	0.6	8.6	2.4	2.4
3.6	2.4	3.6	0.6	0.6
3.6	2.4	3.6	0.6	2.4
3.6	2.4	3.6	2.4	0.6
3.6	2.4	3.6	2.4	2.4
3.6	2.4	8.6	0.6	0.6
3.6	2.4	8.6	0.6	2.4
3.6	2.4	8.6	2.4	0.6
3.84	**2.32**	**6.49**	**1.25**	**1.25**

Note: The mid-range axle spacing combination (i.e., reference vehicle) is shown in bold.