

ADDIS ABABA INSTITUTE OF TECHNOLOGY  
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING



**DETERMINATION OF DYNAMIC LOAD ALLOWANCE  
FACTOR FOR REINFORCED CONCRETE HIGHWAY  
BRIDGES**

**BY: Henok Mulat**

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**“Determination of Dynamic Load Allowance Factor for  
Reinforced Concrete Highway Bridges”**

**By**

**Henok Mulat**

**Approved by the Board of Examiners:**

**Dr. Abrham Gebre**

**Advisor**

\_\_\_\_\_  
**Signature**

\_\_\_\_\_  
**Date**

**Dr.**

**Internal Examiner**

\_\_\_\_\_  
**Signature**

\_\_\_\_\_  
**Date**

**Dr.**

**External Examiner**

\_\_\_\_\_  
**Signature**

\_\_\_\_\_  
**Date**

\_\_\_\_\_  
**Chairperson**

\_\_\_\_\_  
**Signature**

\_\_\_\_\_  
**Date**

## **Declaration**

I certify that this research work entitled “**Determination of Dynamic Load Allowance Factor for Reinforced Concrete Highway Bridges**” is my own work. The work has not been presented elsewhere for assessment and award of any degree. All sources of material used for the research have been duly acknowledged.

Name:            Henok Mulat

Signature:       \_\_\_\_\_

Place:            Addis Ababa University

Institute of Technology

*This Thesis is dedicated to my Mother and Father.*

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# Table of Contents

<b>ACKNOWLEDGEMENT</b> .....	<b>i</b>
<b>LIST OF TABLES</b> .....	<b>v</b>
<b>LIST OF FIGURES</b> .....	<b>vii</b>
<b>ABSTRACT</b> .....	<b>viii</b>
<b>1. INTRODUCTION</b> .....	<b>1</b>
<b>1.1 Background of the Research</b> .....	<b>1</b>
<b>1.2 Motivation of the Research</b> .....	<b>1</b>
<b>1.3 Objectives of the Research</b> .....	<b>2</b>
<b>1.4 Research Questions</b> .....	<b>2</b>
<b>1.5 Scope and Limitations</b> .....	<b>2</b>
<b>1.6 Significance of the Research</b> .....	<b>3</b>
<b>1.7 Methodology</b> .....	<b>3</b>
<b>1.8 Research Outline</b> .....	<b>3</b>
<b>2. LITERATURE REVIEW</b> .....	<b>4</b>
<b>2.1 Bridges</b> .....	<b>4</b>
<b>2.1.1 Reinforced Concrete Bridges</b> .....	<b>4</b>
<b>2.1.2 Classification of Bridges by Span Length</b> .....	<b>5</b>
<b>2.2 Loading Conditions</b> .....	<b>5</b>
<b>2.2.1 Truck Loading</b> .....	<b>5</b>
<b>2.2.2 Tandem Loading</b> .....	<b>6</b>
<b>2.2.3 Lane Loading</b> .....	<b>6</b>
<b>2.3 General Definition of Dynamic Load Allowance Factor</b> .....	<b>7</b>
<b>2.4 National Bridge Code provisions for the Dynamic Load Allowance Factor</b> .....	<b>9</b>
<b>2.4.1 AASHTO Code</b> .....	<b>9</b>
<b>2.4.2 Ontario Code and Canadian Code</b> .....	<b>10</b>
<b>2.4.3 Chinese Code</b> .....	<b>12</b>
<b>2.4.4 New Zealand Code</b> .....	<b>12</b>

2.4.5 Australian Code .....	13
2.4.6 European Code .....	13
2.4.7 British Code.....	14
2.4.8 Japanese Code.....	14
2.4.9 Ethiopian Bridge Design Manual.....	15
2.5 Dynamic Load Allowance Calculation Methods .....	15
2.6 Effect of Vehicle Speed on Dynamic Load Allowance .....	16
<b>3. VERIFICATION OF RESULTS.....</b>	<b>17</b>
3.1 General .....	17
3.2 Flow Chart for Calculation of Static and Dynamic Deflection Using CSI Bridge .....	17
3.3 Verification of Static Analysis.....	18
3.3.1 Static Deflection Using CSI Bridge .....	18
3.3.2 Static Deflection Using Influence Line Method .....	18
3.3.3 Comparison of Static Analysis Results .....	21
3.4 Verification of Dynamic Analysis .....	21
3.4.1 Dynamic Deflection Using CSI Bridge.....	21
3.4.2 Dynamic Deflection Using Analytical Solution .....	22
3.4.3 Comparison of Dynamic Analysis Results.....	28
3.5 Field Investigation .....	28
3.5.1 General .....	28
3.5.2 Field Test Results.....	32
3.5.3 Dynamic Deflection of KOKA Bridge Using CSI Bridge .....	32
3.5.4 Comparison of Field Investigation Results with CSI Bridge.....	33
<b>4. MODELLING AND ANALYSIS FOR THE DETERMINATION OF DYNAMIC LOAD ALLOWANCE FACTOR.....</b>	<b>34</b>
4.1 General .....	34
4.2 Material Property.....	34
4.2.1 Concrete.....	34
4.3. Bridge Dimensioning.....	35
4.3.1 Roadway Width.....	35

4.3.2 Depth Determination .....	35
4.5 Loading Conditions .....	37
4.6 Vehicle Speed .....	39
4.7 Analysis .....	39
4.8 Determination of Dynamic Load Allowance.....	39
<b>5. DEVELOPMENT OF DYNAMIC LOAD ALLOWANCE FORMULA USING REGRESSION ANALYSIS .....</b>	<b>43</b>
5.1 Introduction About Regression Analysis .....	43
5.2 Regression Analysis for Slab Bridges .....	44
5.3 Regression Analysis for T-girder Bridges.....	48
5.4 Regression Analysis for Box-Girder Bridges.....	49
<b>6. CONCLUSIONS AND RECOMMENDATION.....</b>	<b>51</b>
6.1 Conclusion.....	51
6.2 Recommendation.....	51
<b>REFERENCES.....</b>	<b>52</b>
<b>APPENDIX A. FIGURES FOR MODELLING AND ANALYSIS USING CSI BRIDGE</b>	<b>54</b>

## LIST OF TABLES

Table 2.1 IM in AASHTO (2010).....	9
Table 2.2 IM in AASHTO (1989).....	10
Table 2.3 IM in AASHTO LRFD Code (AASHTO 2003a) and Manual for Bridge Evaluation (AASHTO 2011).....	10
Table 2.4 IM in OMT (1991).....	11
Table 2.5 IM in Aust roads (2004).....	13
Table 2.6 Impact Coefficient in JAR (1996).....	15
Table 3.1 Static deflection outputs of both methods.....	21
Table 3.2 The deflection at different times using equation 3.12.....	26
Table 3.3 Dynamic deflection outputs of both methods.....	28
Table 3.4 Effect of Sino truck speed on the dynamic deflection of KOKA bridge.....	32
Table 3.5 Deflection obtained from CSI bridge and field experiment.....	33
Table 4.1 Bridge widths according to their application.....	35
Table 4.2 Depth of slab bridge for different span lengths.....	36
Table 4.3 Slab thickness, web thickness and total depth for different span lengths of T-girder bridges.....	36
Table 4.4 Top and bottom slab thickness, web thickness and total depth for different span lengths of box-girder bridges.....	37
Table 4.5 Dynamic load allowance factors for Slab bridges.....	40
Table 4.6 Dynamic load allowance factors for T-girder bridges.....	41
Table 4.7 Dynamic load allowance factors for Box-girder bridges.....	42
Table 5.1 Input data of Slab bridges for regression analysis.....	44

Table 5.2 Input data of T-girder bridges for regression analysis.....	48
Table 5.3 Input data of Box-girder bridges for regression analysis.....	49

## LIST OF FIGURES

Figure 2.1 Characteristics of the Design Truck.....	6
Figure 2. 2 Design Tandem Load.....	6
Figure 2.3 Dynamic load allowance factor in OHBDC (data from OMTC 1983).....	11
Figure 3.1 Position of tandem load for simply supported 10m slab bridge.....	19
Figure 3.2 Simple beam concentrated load at $x = a$ .....	19
Figure 3.3 Representation of the vehicle as single concentrated moving load and half- sine pulse load Vs. time graph.....	22
Figure 3.4 Plot of deflection Vs. time.....	28
Figure 3.5 Koka bridge superstructure cross section.....	29
Figure 3.6 Installed deflection measuring tool at mid span of the bridge.....	30
Figure 3.7 Heavy truck with multiple axle load carrying 172-Ton transformer approaches and passes the bridge with a crawling speed of 4Kmh.....	30
Figure 3.8 Sino trucks carrying full of sand material passes on the bridge with different speeds....	31
Figure 3.9 Measured axle weight of Sino truck from weighing station.....	31
Figure 3.10 Koka bridge model.....	33
Figure 3.11 Field investigation Vs. CSI bridge output.....	33
Figure 4.1 Vehicle live loads in different codes.....	38
Figure 4.2 Measured axle load and spacing of Sino trucks.....	38
Figure 5.1 Effect of span length on the dynamic load allowance factor for Slab bridges.....	45
Figure 5.2 Effect of speed on the dynamic load allowance factor for Slab bridges.....	45

## **ABSTRACT**

Accounting the dynamic effect of vehicles using the dynamic load allowance factor has been widely accepted in bridge engineering. However, consensus on the evaluation of the dynamic load allowance factor is yet to be reached and this is because large number of parameters affects the dynamic load allowance factor. Bridge span length, fundamental frequency of the bridge and vehicle, bridge type, bridge material, damping, vehicle speed, vehicle weight, number of axles, number of vehicles and vehicle loading position are the parameters used to study the dynamic load allowance factor by different researchers and national bridge codes.

Many national bridge codes have stated different provisions for the dynamic load allowance (DLA) factor. The different codes have specified the DLA factor in terms of bridge span length, as a function of road surface condition, based on different limit states, bridge fundamental frequency and design loading configurations. This indicates significant variation in bridge code provisions for dynamic load allowance factor exists and this thesis paper tries to asses and determine new appropriate dynamic load allowance formula for reinforced concrete Slab and Girder highway bridges.

In this study, a complex finite element software called CSI Bridge 20 is used. In modelling; standard bridge lane width, different span length for both Slab and Girder bridges, design loading configurations and vehicle speeds used to determine the appropriate dynamic load allowance factor.

Moving load analysis is done to get the static response and time history analysis is done to get the dynamic response. The static analysis using the finite element software is validated using influence line method and the dynamic analysis is validated using analytical solution and field investigation conducted on KOKA bridge.

Finally, new dynamic load allowance formula is set as a function of bridge span length and vehicle speed using regression analysis. Conclusions and recommendations drawn based on the research findings.

## **1. INTRODUCTION**

### **1.1 Background of the Research**

In the design of bridges considering dynamic effect resulting from the movement of vehicles is very important. To account for such a dynamic effect, it is required that the static live (vehicular) load be increased by a dynamic load allowance (DLA) factor [1]. The basic definition of dynamic load allowance factor is the ratio of maximum dynamic response to maximum static response.

Agreement on the evaluation of dynamic load allowance is not yet reached. Many researches shown that the evaluation of the DLA is difficult task because it is affected by a large number of parameters [2]. Bridge span length, fundamental frequency of the bridge and vehicle, bridge type, bridge material, damping, vehicle speed, vehicle weight, number of axles, number of vehicles and vehicle loading position are the parameters used to study the dynamic load allowance factor by different researchers and national bridge codes.

Many national bridge codes have different provisions for the dynamic load allowance factor, DLA.

### **1.2 Motivation of the Research**

Bridge span length and fundamental frequency are the main influencing parameters adopted in design codes for dynamic load allowance factor. In this research, other parameters like loading conditions (Sino truck and tandem) and speed of vehicles considered and their effect in the determination of the dynamic load allowance factor studied.

Most bridge codes don't distinguish dynamic load allowance factor for different bridge materials despite the fact that material property differ for different materials. In this research, the most widely used construction material in the world and Ethiopia that is reinforced concrete is used for the determination of the dynamic load allowance formula.

Most bridge codes don't clearly specify the dynamic load allowance factor for different bridge types. In this research, the most preferable bridge types in Ethiopia that are Slab, T-girder and Box-girder bridges is considered and new dynamic load allowance formula is developed for each type of bridges separately.

Significant variation in bridge code provisions for dynamic load allowance factor exists. In this research, appropriate dynamic load allowance formula for Slab and Girder reinforced concrete highway bridges is developed.

### **1.3 Objectives of the Research**

The general objective of this research is to set new dynamic load allowance formula for slab, T-girder and Box-girder reinforced concrete highway bridges.

The Specific Objectives of this research are:

- To investigate the effect of speed of vehicles, loading conditions and bridge types on the dynamic load allowance factor.
- To compare the research output to the national bridge design codes and specifications.
- To provide a speed limit in Ethiopian highway bridges.
- To study the response of reinforced concrete bridges to the dynamic load.

### **1.4 Research Questions**

1. Does the speed of vehicles, loading condition and bridge types has effect on the determination of dynamic load allowance factor?
2. The values specified for dynamic load allowance for Ethiopian Bridge Design Manual 2013; is it safe for tandem and Sino truck loading?
3. To what extent the speed of vehicles affects the dynamic load allowance factor?

### **1.5 Scope and Limitations**

The scope of this research is to determine the dynamic load allowance factor for reinforced concrete slab, T-girder and Box-girder highway bridges.

The research work has some limitations. These are:

1. Parameters like roadway roughness, damping and traffic flow are not considered.
2. Only reinforced concrete material is considered in the research.
3. Only Slab, T-girder and Box-girder bridge types are considered in the research.

## 1.6 Significance of the Research

- Bridge designers can use the developed dynamic load allowance formulas during design of slab and Girder reinforced concrete highway bridges.
- It is an input for the revision of Ethiopian Bridge Design Manual 2013 section 3.6.2.
- It is an input for provision of speed limit in Ethiopian highway bridges.

## 1.7 Methodology

The methodologies adopted in this research to achieve the objectives are outlined as follows:

1. Applicable practices, research findings and other relevant information on dynamic load allowance for reinforced concrete highway bridges is evaluated and reviewed.
2. Relevant literatures on dynamic load allowance for highway bridges is reviewed.
3. A finite element software CSI Bridge 20 is used for modelling and analysis.
4. Influence line method is used for verification of static analysis. Analytical solution and field investigation on KOKA bridge was conducted to verify the dynamic analysis.
5. A multiple linear regression analysis is used to determine the dynamic load allowance formula.

## 1.8 Research Outline

This thesis has six chapters and the present chapter; chapter one deals about the background, motivation, objective, scope, limitation and significance of the research.

Chapter two describes the state-of-the-art review on national bridge codes provision for the dynamic load allowance factor, dynamic load allowance calculation methods and different research findings on dynamic load allowance.

Chapter three is about verification of results. The static analysis is verified using influence line method. The dynamic load analysis is verified using analytical solution and field on investigation on KOKA bridge.

Chapter four deals on modelling and analysis of both Slab and Girder reinforced concrete highway bridges using CSI Bridge 20.

Chapter five deals on the development of dynamic load allowance formula using multiple linear regression analysis.

Chapter six deals on conclusions and recommendations based on the research findings.

## **2. LITERATURE REVIEW**

### **2.1 Bridges**

Bridges are very essential structures to pass obstacles. The obstacles may be a river, valley, road and railway. Bridges affect peoples. Peoples use them, engineers design them and later build and maintain them. Before they constructed, they must be planned and engineered [3].

A bridge is a basic element in a transportation system for three reasons.

- It controls the capacity of the transportation system.
- Bridges are expensive structures.
- If it fails, the transportation system will fail.

Because a bridge is a basic element due to the above three reasons, balance must be achieved between handling future traffic volume, loads and the cost of a heavier and wider bridge structures. Strength is always a primary consideration but so should measures to prevent deterioration [3].

#### **2.1.1 Reinforced Concrete Bridges**

Because of its economy in short and medium spans, durability, low maintenance costs, and easy adaptability to horizontal and vertical curvature reinforced concrete is the most widely used material in highway bridges. The principal types of cast-in-place supporting elements are the longitudinally reinforced slab, T beam or girder, and cellular or box girder.

The raw materials of concrete, consisting of water, fine aggregate usually sand, coarse aggregate either gravel or crashed stone and cement can be found in most areas of the world and can be mixed to form a variety of structural shapes. The great availability and flexibility of concrete material and reinforcing bars than steel sections have made the reinforced concrete bridges preferable in Ethiopia. Since, fabrication and importing steel is very expensive, reinforced concrete is an excellent choice [4].

Bridges with minimum number of spans, fewest deck joints and widest spacing of girders are most economical. By reducing the number of spans, the construction cost of one pier is eliminated. Deck joints are a high maintenance cost item, so minimizing their number will reduce the life cycle cost of the bridge [4].

Advantages of reinforced concrete bridges.

- Adaptability of concrete in wide variety of structural shapes
- Low maintenance cost
- They possess long life and better resistance to temporary overloads and dynamic loads
- Cast-in-place reinforced concrete structures are continuous and monolithic, these lead to easy construction, low cost and good seismic resistance.
- Desired aesthetic appearance can be achieved.

The disadvantage

- Heavy dead load
- Difficulty to widen
- Large construction time
- Requires form work and false work

### **2.1.2 Classification of Bridges by Span Length**

Based on span length bridges are classified as short span, medium span and long span. A common practice to classify bridges by span length in the absence any established criteria is given below.

- Culverts < 6m
- Short- span bridges 6-38m
- Medium-span bridges 28-120m
- Long-span bridges over 120m

## **2.2 Loading Conditions**

### **2.2.1 Truck Loading**

According to the Ethiopian Roads Authority, Bridge Design Manual 2002, the weights and spacings of axles and wheels for the design truck shall be specified in the Figure shown below. The spacing between the two 145 KN axles shall be varied between 4.3 and 9.0 m to produce extreme force effects.

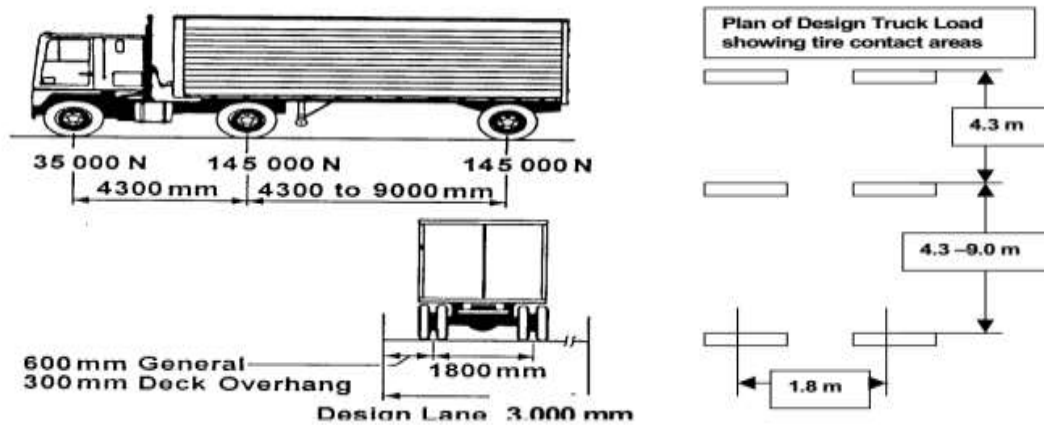


Figure 2.1 Characteristics of the Design Truck

### 2.2.2 Tandem Loading

According to the Ethiopian Roads Authority, Bridge Design Manual 2002, the design tandem used for Strategic Bridges shall consist of a pair of 110 kN axles spaced 1.2 m apart. The transverse spacing of wheels shall be taken as 1.8 m. strategic bridges are bridges across wide, flowing rivers (Blue Nile, Awash, Omo) which cannot easily be replaced by a temporary bridge such as a 40 m span double Bailey truss bridge. The spacing and loading is illustrated in the figure below.

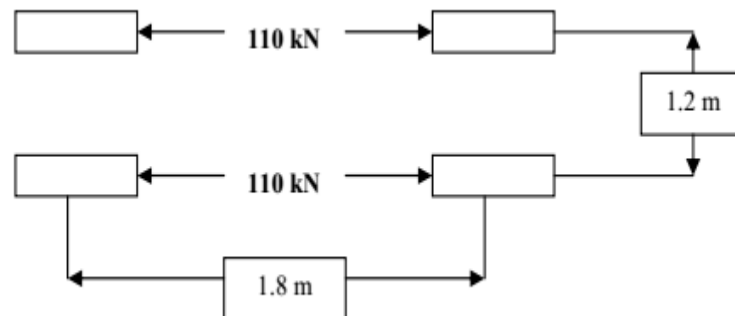


Figure 2.2 Design Tandem Load

### 2.2.3 Lane Loading

According to the Ethiopian Roads Authority, Bridge Design Manual 2002, the design lane load shall consist of a load of **9.3 kN/m**, uniformly distributed in the longitudinal direction. Transversely, the design lane load shall be assumed to be uniformly distributed **over a 3.0-m width**. The force effects from the design lane load shall not be subject to a dynamic load allowance.

### **2.3 General Definition of Dynamic Load Allowance Factor**

The road way surface is not completely smooth, implies the vehicle suspension must react to road way roughness by compression and extension of the suspension system. This oscillation will create axle forces that exceed the static weight during the acceleration is upward and is less than the static weight when the acceleration is downward. While commonly called impact, the phenomenon is mentioned to as dynamic loading. There have been many experimental and analytical studies conducted to determine the dynamic load effect [3].

There are different calculation methods for bridges according to the existing dynamic load allowance (DLA) methods; these are, conventional DLA definition, the experimental method and design codes (specifications) provision method and the proposed DLA methods of their own research based on two approaches; the maximum and its corresponding response method (Approach 1) and Weighted average method (Approach 2). According to Design codes (specifications) provisions method the dynamic load allowance in majority of cases is specified by three different ways; span length of the bridge, natural frequency of the bridge, and a constant value. As an example, stated in the research paper, AASHTO standard specification in USA Washington (DC); 2002 and KBDS in Korea expressed DLA as a function the bridge length. The Chinese Bridge Code (2004) considers DLA as a function of the flexural natural frequency of the bridge. In AASHTO LRFD (2012), DLA is a constant value. In Canada, DLA is based on the number of truck axles passing over the bridge [6].

In AASHTO LRFD bridge design specification 2010 and ERA bridge design manual 2013 use a constant value in table format for different limit states as shown in table 2.1. The factor to be applied to the static load shall be taken as;  $(1+IM/100)$ . IM is an increment to be applied to the static wheel load impact from moving vehicles. According to AASHTO LRFD bridge design specification 2010, the dynamic effects due to moving vehicles may attribute to two sources: one is Hammering effect; hammering effect is the dynamic response of the wheel assembly to riding surface discontinuities, such as deck joints, cracks, potholes, and delamination's. second, dynamic response of the bridge as a whole to passing vehicles, which may be due to long undulations in the roadway pavement, such as those caused by settlement of fill, or to resonant excitation as a result of similar frequencies of vibration between bridge and vehicle. Field tests indicate that in the majority of highway bridges, the dynamic component of the response does not exceed 25 percent

of the static response to vehicles. This is the basis for dynamic load allowance with the exception of deck joints. However, the specified live load combination of the design truck and lane load, represents a group of exclusion vehicles that are at least  $\frac{4}{3}$  of those caused by the design truck alone on short and medium span bridges. The specified value of 33 percent in table 2.1 is the product of  $\frac{4}{3}$  and the basic 25 percent. The limitation on the dynamic load allowance reflects the fact that deck surface roughness is a major factor in vehicle bridge interaction and that is difficult to estimate long term deck deterioration effects thereof at the design stage. Proper application to the provision for reducing the dynamic load allowance is:  $IM_{\text{Calculated}} \geq 0.5 IM_{\text{Table 2.1}}$ . when analysis for dynamic interaction between a bridge and the live load is required, the owner shall specify and/or approve surface roughness, speed and dynamic characteristics of the vehicle to be employed for the analysis. The dynamic load allowance shall not be applied to retaining walls not subject to vertical reactions from the superstructure, and foundation components that are entirely below ground level.

A new impact formula is developed in terms of a nondimensional speed parameter. It is shown that many bridge codes, including the American Associations of State Highways and Transportation officials (AASHTO) Specifications (standard 1989) and the Ontario Code (Ontario 1983), have adopted the same impact formula for various dynamic responses, and have related the impact factor to a single parameter of the bridge, such as the span length or frequency of vibration. In their belief this approach to design is certainly an over simplification and, in many cases, misrepresentation of the complex physical phenomenon in the vehicle-bridge interactions. Other parameters that may affect the impact factor include the velocity and dynamic properties of the moving vehicle, the dynamic properties and boundary conditions of the bridge and the roughness in road pavement considered and by modeling the vehicle as sprung masses and a bridge structure as beam elements, a parametric study is performed for various simple and continuous beams traversed by five axle trucks. A non-dimensional speed parameter  $s$  is then defined and a formula for determining impact factor for deflections, bending moments and shear forces presented in terms of the non-dimensional speed parameter,  $s$ . Finally, the code-based specifications compared with the new formulas obtained from the study [9].

Due to deterioration of existing bridges, the impact values stated in the codes may underestimate the impact factors [10].

## 2.4 National Bridge Code provisions for the Dynamic Load Allowance Factor

Different provisions for the dynamic load allowance factor, IM have been specified by many national bridge codes [2]. In this section, different national bridge code provisions for the dynamic load allowance factor is reviewed. The provisions are applied only to bridge superstructures.

### 2.4.1 AASHTO Code

The AASHTO (1992) standard specifications for highway bridges have specified the IM as a function of the bridge span length and given by the following equation.

$$IM = \frac{15.24}{L + 38.10} \leq 0.3 \quad (2.1)$$

Where, L=bridge span length (in meters)

For both truck and lane loads the IM is applied. In the AASHTO (1994) LRFD Bridge design specifications, the term DLA was used to replace the IM. In the AASHTO (2010) LRFD code, the DLA is specified based on different limit states and components. Unlike the specifications in the standard specifications, the IM is independent of the bridge span length and is applied to truck and tandem loads excluding lane load. The AASHTO (2010) LRFD code specification for the dynamic load allowance factor is shown below in table 2.1.

Table 2.1 IM in AASHTO (2010)

component	IM
Deck Joints- All limit states	75%
All other components	
• Fatigue and Fracture limit state	15%
• All other Limit States	33%

In addition to bridge design, the AASHTO (1989) Guide specification for strength Evaluation of Existing Steel and Concrete Bridges specifies the IM as a function of road surface condition for load rating existing bridges as shown in table 2.2.

Table 2.2 IM in AASHTO (1989)

Wearing surface		
Condition	Description	IM
Good	No repair required	0.1
Fair	Minor deficiency, item still functioning as designed	0.1
Poor	Major deficiency, item in need of repair to continue functioning as designed	0.2
Critical	Item no longer functioning as designed	0.3

It can be seen from table 2.2 that, as the road surface condition worsens the IM value increases.

The IM value 0.33 stated for the strength and service limit states to account for the dynamic effects induced by moving vehicles in AASHTO (2003a) Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) is intentionally conservative considering certain distressed approach and bridge deck conditions. Consequently, for longitudinal members having spans greater than 12.19m and less severe approach and deck surface conditions the IM may be reduced. Table 2.3 shows reduced IM value according to riding surface condition.

Table 2.3 IM in AASHTO LRFD Code (AASHTO 2003a) and Manual for Bridge Evaluation (AASHTO 2011)

Riding Surface condition	IM
Smooth riding surface at approaches, bridge deck, and expansion joints	0.1
Minor surface deviations or depressions	0.2

#### 2.4.2 Ontario Code and Canadian Code

The Ontario Highway Bridge Design Code (OHBDC) {Ontario Ministry of Transportation and Communications (OMTC) 1983} specifies the IM based on the first flexural mode frequency of the bridge, as shown in figure 2.2.

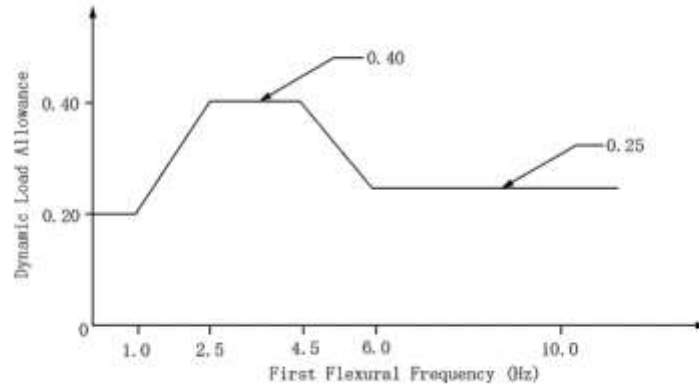


Figure 2.3 Dynamic load allowance factor in OHBDC (data from OMTC 1983)

Between frequencies 2-5Hz maximum IM value is assigned and this is because the frequency range covers the common frequency of vehicle bouncing and this matching of vehicle and bridge frequencies lead to quasi-resonance, inducing a maximum dynamic response on the bridge. The provisions for the IM in the OHBDC (OMT 1991) are majorly different from the Previous edition. The OHBDC (OMT 1991) specifies the IM as a function of the number of axles of the vehicle as shown in the table 2.4 below.

Table 2.4 IM in OMT (1991)

Number of axles	IM
1	0.4
2	0.3
3 or more	0.25

The provision takes in to consideration the fact that heavier vehicles, which usually have more axles, usually have lower IMs.

In the Canadian Highway Bridge Design Code (CHBDC) {Canadian Standards Associations (CSA) 2006}, the IM is also dependent on the number of axles, and is applied to the CL-W truck, which is an idealized five-axle truck used for the purpose of design. The provisions are the same as the OHBDC (OMT 1991).

### 2.4.3 Chinese Code

The General Code for Design of Highway Bridges and Culverts {Ministry of Transport of the Peoples Republic of China (MTPRC) 1989} by the Chinese Ministry of Transport Specifies IM as a function of the bridge span length.

IM is calculated using the following expressions for the main structural members of concrete bridges.

$$\begin{aligned}
 & 0.3 && \text{for } L \leq 5 \text{ m} \\
 \text{IM} = & 0.3 \times (1.125 - 0.025L) && \text{for } 5 \text{ m} < L < 45 \text{ m} \\
 & 0 && \text{for } L \geq 45 \text{ m}
 \end{aligned} \tag{2.2}$$

For the main structural members of steel bridges, the IM is specified as

$$\text{IM} = \frac{15}{37.5 + L} \tag{2.3}$$

where L = bridge span length in meters. However, IM is specified as a function of the fundamental frequency of bridges in the 2004 edition of the General Code for Design of Highway Bridges and Culverts (MTPRC 2004).

$$\begin{aligned}
 & 0.05 && \text{for } f \leq 1.5 \text{ Hz} \\
 \text{IM} = & 0.1767 \ln f - 0.0157 && \text{for } 1.5 \text{ Hz} < f < 14 \text{ Hz} \\
 & 0.45 && \text{for } f \geq 14 \text{ Hz}
 \end{aligned} \tag{2.4}$$

where  $f$  = fundamental frequency of bridges.

### 2.4.4 New Zealand Code

The **dynamic load factor (DLF)** which is equal to 1+ IM is specified based on bridge span length in the New Zealand Transport Agency (NZTA 2013) Bridge Manual. A constant value of 1.30 is given for moments in cantilevers and deck slabs, reactions and shears. For moments in simple and continuous spans, the DLF is given as a function of the bridge span length as follows:

$$DLF = 1 + \frac{15}{L+38} \quad \text{for } L > 12 \text{ m} \quad (2.5)$$

1.30      for       $L \leq 12 \text{ m}$

Where L=bridge span length (in meters) for positive moments and the average of adjacent span lengths for negative moments.

### 2.4.5 Australian Code

Traffic load configurations are the bases for determination of IM in the Aust roads (2004) AS 5100 Bridge Design Standard-part 2: Design Load, the IM, which applies to both truck and uniformly distributed lane (UDL) loads. The table below shows the DLA value for different traffic configurations.

Table 2.5 IM in Aust roads (2004)

Traffic Load Configurations	Description	IM
Wheel load, W80	Single Wheel load of 80 KN	0.4
Axle load, A160	Two W80 wheel loads	0.4
Triaxle group, M1600	Combination of axle group and lane UDLs	0.35
Moving load, M1600	Combination of axle group and lane UDLs	0.3
Stationary load, S1600	Combination of axle group and lane UDLs	0
Heavy load platform load	Heavy load platform	0.1

### 2.4.6 European Code

Based on a medium pavement quality and pneumatic vehicle suspension the dynamic allowance factor (DAF) is specified as a function of the bridge span length for one-, two-, and four-lane bridges in Eurocode 1: Actions on structures—part 2: Traffic Loads on Bridges (CEN 2003).

*For one-lane bridges*, the DAF for moment is specified as

$$DAF = \begin{cases} 1.7 & \text{for } L \leq 5 \text{ m} \\ 1.85 - 0.03L & \text{for } 5 \text{ m} < L < 15 \text{ m} \\ 1.4 & \text{for } L \geq 15 \text{ m} \end{cases} \quad (2.6)$$

and the DAF for shear is specified as

$$\begin{aligned}
 & 1.4 && \text{for} && L \leq 5 \text{ m} \\
 \text{DAF} = & 1.45 - 0.03L && \text{for} && 5 \text{ m} < L < 25 \text{ m} \\
 & 1.2 && \text{for} && L \geq 25 \text{ m}
 \end{aligned} \tag{2.7}$$

*For two lane bridges*, the DAF for both moment and shear is specified as

$$\begin{aligned}
 \text{DAF} = & 1.3 - \frac{0.4}{100}L && \text{for} && L \leq 50 \text{ m} \\
 & 1.1 && \text{for} && L > 50 \text{ m}
 \end{aligned} \tag{2.8}$$

Where  $L$  = bridge span length in meters. For four-lane bridges, the DAF for both moment and shear is specified a constant value of 1.1. But, under some unfavorable conditions, like locations near expansion joints, additional amplification factor  $\Delta\phi$  needs to be considered.

$$\Delta\phi = 1.31 - \frac{D}{26} \quad \text{for} \quad \Delta\phi \geq 1 \tag{2.9}$$

Where  $D$  = distance in meters from the location of the considered cross section to the expansion joint.

#### 2.4.7 British Code

Two types of loading for highway bridges are considered, namely, the HA and HB loading for normal and abnormal traffic loads, respectively in BS 5400-2, Steel, Concrete and Composite Bridges. Part 2: Specification for Loads {British Standards Institute (BSI) 2006}. In both loading types an IM value of **0.25** is included in the design load.

#### 2.4.8 Japanese Code

IM is given as a function of bridge span length for different loading conditions in Specifications for Highway Bridges by the Japan Road Association (JRA 1996). The expressions for the IM are similar to the format given in the AASHTO standard specifications. The IM for truck loading is specified as the same for all types of bridges while the IM for lane loading varies with different types of bridges. The table below shows the impact coefficient in JRA (1996).

Table 2.6 Impact Coefficient in JAR (1996)

Bridge type	Loading type	IM
Steel	Truck and lane	$20/(50+L)$
Reinforced Concrete	Truck	$20/(50+L)$
	Lane	$7/(20+L)$
Prestressed Concrete	Truck	$20/(50+L)$
	Lane	$10/(25+L)$

Where L = Bridge span length in meters.

### 2.4.9 Ethiopian Bridge Design Manual

The Ethiopian Roads Authority, Ethiopian Bridge design manual 2013 is adopted from the AASHTO (2010). The provision is shown in table 2.1.

### 2.5 Dynamic Load Allowance Calculation Methods

As discussed in section 2.3, different calculation methods for bridges according to the existing dynamic load allowance methods and the proposed DLA methods of their own research based on two approaches; the maximum and its corresponding response method (Approach 1) and Weighted average method (Approach 2). The conclusions drawn from their study are mentioned below [6].

1. The relationship between the vehicle speed and DLA is not obvious in their study even if it is a simply-supported beam bridge. So, the formula of DLA is suggested to ignore the impact of vehicle speed.
2. The DLA obtained from the proposed approaches are greater than those obtained by the conventional definition and experimental methods, which shows that the current conventional DLA computing methods may underestimate the dynamic response of the structure.
3. All the results in their study demonstrated that the deflection DLAs are different from bending moment ones. They present that in most cases the DLA is utilized to satisfy the requirement at strength limit state so they suggested to measure bending moment DLA instead of deflection DLA when evaluating the bridge.
4. They recommend to use the weighted average principle based on experimental method to calculate DLA, since it can reflect the vehicles whole impact on the bridge.

## 2.6 Effect of Vehicle Speed on Dynamic Load Allowance

The conclusions drawn from different researchers on the effect of vehicle speed on the DLA is mentioned as follows:

The speed is linearly proportional to the dynamic load allowance factor and as the speed increases the impact factor also increases; essential to their study is the implementation of a non-dimensional speed parameter  $S$ , which is defined as the ratio of the driving frequency of the vehicle, as represented by  $\pi v/L$ , with  $v$  denoting the velocity of the vehicle and  $L$  the characteristic length of the beam, to the fundamental frequency  $\omega$  of the beam. They finally propose an impact formula in terms  $S$  for deflection, bending moment and shear forces [1].

vehicle speed has no effect on the dynamic load allowance factor provision due to two main reasons. One, impact factors jump up and down as the vehicle speed increases from 30Km/h to 120Km/h. Secondly, ideally vehicles can drive at speeds within a wide range [10].

By using simple numerical models to study the effect of vehicle velocity on a bridges dynamic amplification and by modelling the single vehicle as a constant point force crossing a simply supported bridge, they concluded that as the crossing velocity increases the dynamic amplification oscillates between high and low values [11].

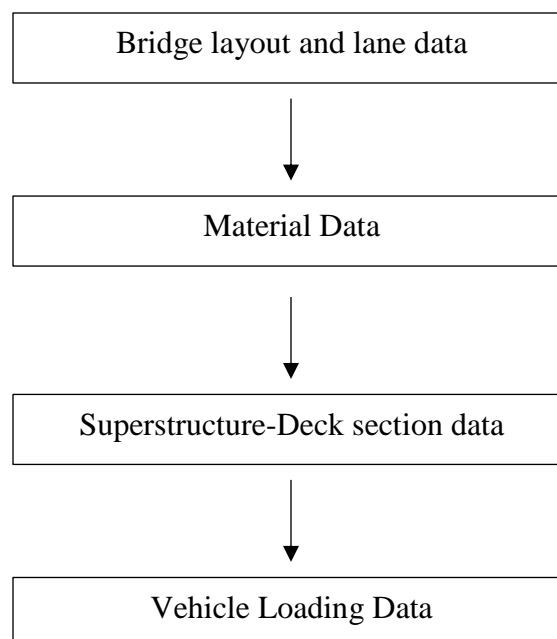
### 3. VERIFICATION OF RESULTS

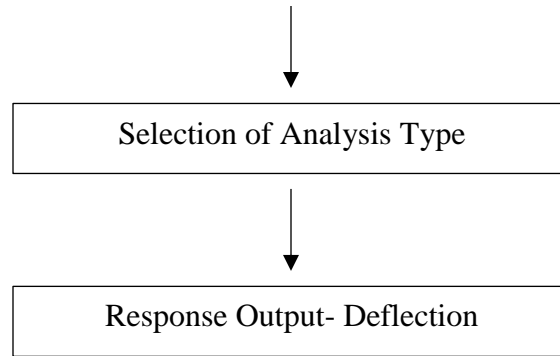
#### 3.1 General

Moving load analysis using CSI Bridge is done to get the maximum static responses of the slab and Girder bridges. Time history analysis using CSI Bridge is done to get the maximum dynamic responses of the slab and Girder bridges; mid span deflection is selected for computation of dynamic load allowance (DLA) factor. Tandem vehicle loading for Slab bridges and Sino truck vehicle loading for Girder bridges is used for verification and determination of DLA factor. The result of the CSI Bridge is verified using the influence line method for the static analysis. The result of the CSI Bridge is verified using analytical solution and field investigation conducted on KOKA bridge.

#### 3.2 Flow Chart for Calculation of Static and Dynamic Deflection Using CSI Bridge

The flow chart for the analysis of bridges for static and dynamic loads are presented in this section. Only flow chat to show the steps used to get the maximum static and dynamic deflection at mid span of the bridge using CSI Bridge is presented here. Detailed figures for static and dynamic analysis using CSI Bridge is presented in the Appendix A.





### 3.3 Verification of Static Analysis

#### 3.3.1 Static Deflection Using CSI Bridge

The input parameters for verification of results of the CSI Bridge for computation of static deflection is given below.

- Concrete strength,  $f'_c = 20\text{Mpa}$
- Roadway width,  $R_w = 7.32\text{m}$
- Clear span of the bridge,  $C_s = 10\text{m}$
- Depth of Slab,  $D = 0.6\text{m}$
- Vehicle load = design tandem load with a pair of 110KN axles spaced 1.2m apart.
- Vehicle allowed to move in forward direction at a crawling speed in right lane.

Then, moving load analysis case is set to run to get the maximum static response at mid span of the 10m slab bridge. **2.177mm** is the deflection obtained at mid span of the bridge from the finite element software.

#### 3.3.2 Static Deflection Using Influence Line Method

Influence lines are the most important concept used in the analysis of structures subjected to variable loads or moving loads. The concept of influence line was initially introduced by E. Winkler in 1867. A graph of response function of a structure as a function of the position of a downward unit load crossing the structure is termed as influence line. Analysis of structures for moving loads consists of two steps [12]:

1. Determine the position of the load where maximum response obtained.
2. Compute the maximum value of the response function.

In our case, for tandem load the position of the load is symmetric; so, placing the axle loads equal distance from the point of mid span as shown in the figure below produces maximum response.

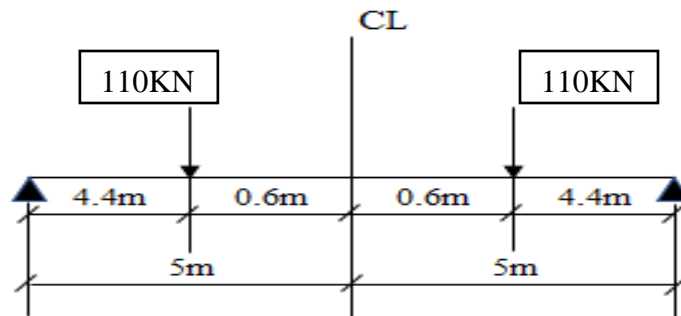


Figure 3.1 Position of tandem load for simply supported 10m slab bridge

The deflection equation for the loading condition shown in figure 3.2 is given below. The deflection of the beam caused by several different loads acting simultaneously can be found by superimposing the deflections caused by the loads acting separately.

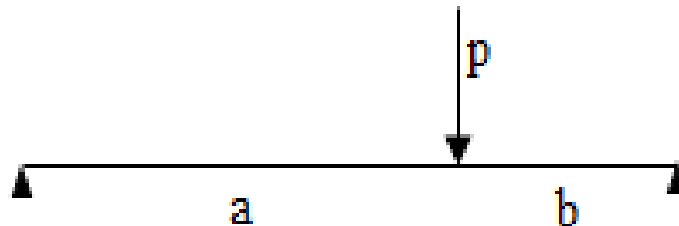


Figure 3.2 Simple beam concentrated load at  $x = a$

$$\text{Deflection}(\Delta): - \frac{pbx}{6LEI} (L^2 - b^2 - x^2) , \quad 0 \leq x \leq a \quad (3.1)$$

$$\frac{pbx}{6LEI} (L^2 - b^2 - x^2) + \frac{p(x-a)^3}{6EI} , \quad a \leq x \leq L$$

$$\text{For } \Delta_1: a = 4.4m \quad b = 5.6m \quad L = 10m$$

$$\text{For } \Delta_2: a = 5.6m \quad b = 4.4m \quad X = 5m$$

*Deflection  $\Delta_1$*

$$\begin{aligned} L^2 - b^2 - x^2 &= (10m)^2 - (5.6m)^2 - (5m)^2 \\ &= 100m^2 - 31.36m^2 - 25m^2 \\ &= 43.64m^2 \end{aligned}$$

$$6L = 6 \times 10m = 60m$$

$$pbx = 110kn \times 5.6m \times 5m = 3,080knm^2$$

$$\begin{aligned} \Delta_1 &= \frac{Pbx}{6LEI} (L^2 - b^2 - x^2) \quad 0 \leq x = 5m \leq a = 4.4m \\ &= \frac{3,080knm^2 \times 43.64m^2}{60m \times EI} = \frac{2,240.186667knm^3}{EI} \end{aligned}$$

*Deflection  $\Delta_2$*

$$\begin{aligned} L^2 - b^2 - x^2 &= (10m)^2 - (4.4m)^2 - (5m)^2 \\ &= 100m^2 - 19.36m^2 - 25m^2 \\ &= 55.64m^2 \end{aligned}$$

$$(x - a)^3 = (5m - 5.6m)^3 = -0.216m^3$$

$$Pbx = 110kn \times 4.4m \times 5m = 2,420knm^2$$

$$\begin{aligned} \Delta_2 &= \frac{Pbx}{6LEI} (L^2 - b^2 - x^2) + \frac{p(x - a)^3}{6EI} \quad a = 5.6m \leq x = 5m \leq L = 10m \\ &= \frac{2,420knm^2}{60m \times EI} \times 55.64m^2 - \frac{110kn \times 0.216m^3}{6EI} \\ &= \frac{2,244.146667knm^3}{EI} - \frac{3.96knm^3}{EI} = \frac{2,240.186667knm^3}{EI} \end{aligned}$$

$$\Delta = \Delta_1 + \Delta_2 = \frac{4,480.373334knm^3}{EI}$$

*Calculation of flexural stiffness(EI)*

*E = 30Gpa for C20 / 25 concrete.*

$$I = \frac{bh^3}{12} \text{ for rect an gular section, Lane width of the bridge}(b) = 3.66m$$

$$\text{Total depth of the bridge}(h) = 0.6m$$

$$I = \frac{3.66m \times (0.6m)^3}{12} = 0.06588m^4$$

$$EI = 30Gpa \times 0.06588m^4 = 1.9764 \times 10^6 knm^2$$

$$\text{Total deflection using superposition principle, } \Delta = \Delta_1 + \Delta_2 = \frac{4,480.373334knm^3}{EI}$$

$$\Delta = \frac{4,480.373334knm^3}{1.9764 \times 10^6 knm^2} = 2.266mm$$

### 3.3.3 Comparison of Static Analysis Results

The deflection output of both methods is shown in the table below.

Table 3.1 Static deflection outputs of both methods.

CSI Bridge mid span deflection output (mm)	Influence line method mid span deflection output (mm)	Accuracy (%)
2.177	2.266	96.1

## 3.4 Verification of Dynamic Analysis

### 3.4.1 Dynamic Deflection Using CSI Bridge

The input parameters for verification of results of the CSI Bridge for computation of dynamic deflection is given below.

- Concrete strength,  $f'_c = 20\text{Mpa}$
- Roadway width,  $R_w = 7.32\text{m}$
- Clear span of the bridge,  $C_s = 10\text{m}$
- Depth of Slab,  $D = 0.54\text{m}$
- Vehicle load = design tandem load with a pair of 111.2056KN axles spaced 1.2192m apart.
- Speed of vehicle = 40KMH

Then, Time history analysis case is set to run to get the maximum dynamic response at mid span of the 10m slab bridge. **1.586mm** is the deflection for entire bridge section obtained at mid span of the bridge from the finite element software.

### 3.4.2 Dynamic Deflection Using Analytical Solution

The equation of motion for the generalized system is given by the equation [13]:

$$\tilde{m}\ddot{z} + \tilde{c}\dot{z} + \tilde{k}z = \tilde{p}(t) \quad (3.2)$$

$$u(x,t) = \Psi(x)z(t) \quad (3.3)$$

Where,  $\Psi(x)$  is the shape function. The shape function can be known from the configuration of the system and must satisfy the displacement boundary conditions.  $z(t)$  is associated generalized displacement.

$\tilde{m}$ ,  $\tilde{c}$ ,  $\tilde{k}$ ,  $\tilde{p}(t)$  are defined as generalized mass, generalized damping, generalized stiffness and generalized force of the system. The figure below shows the presentation of the vehicle moving with velocity on simply supported bridge.

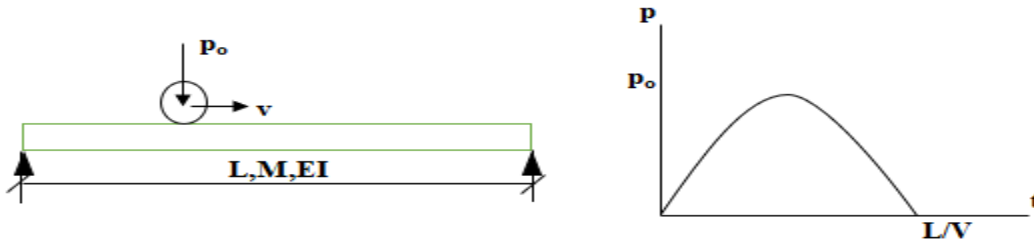


Figure 3.3 Representation of the vehicle as single concentrated moving load and half- sine pulse load Vs. time graph

Assumption neglect damping and shape function  $\Psi(x) = \sin\left(\frac{\pi x}{L}\right)$

1. We now determine the generalized mass, stiffness and natural frequency

$$\Psi(x) = \sin\left(\frac{\pi x}{L}\right)$$

$$\Psi'(x) = \frac{\pi}{L} \cos\left(\frac{\pi x}{L}\right) \quad (3.4)$$

$$\Psi''(x) = -\frac{\pi^2}{L^2} \sin\left(\frac{\pi x}{L}\right)$$

$$\tilde{m} = \int_0^L m \sin^2 \frac{\pi x}{L} dx = \frac{mL}{2} \quad (3.5)$$

$$\tilde{k} = \int_0^L EI \left(\frac{\pi^4}{L^4} \sin^2 \frac{\pi x}{L}\right) dx = \frac{\pi^4 EI}{2L^3} \quad (3.6)$$

$$\omega_n = \frac{\tilde{k}}{\tilde{m}} = \frac{\pi^2}{L^2} \sqrt{\frac{EI}{m}} \quad (3.7)$$

2. We now determine the generalized force. A load  $P_0$  traveling with a velocity  $V$  takes time  $t_d = L/V$  to cross the bridge. The moving vehicle load can be described mathematically as

$$p(x, t) = \begin{cases} \frac{u(t)}{(u_{st})_o} = \frac{1}{1 - (T_n / 2t_d)^2} \times \left( \sin\left(\pi \frac{t}{t_d}\right) - \frac{T_n}{2t_d} \left(2\pi \frac{t}{T_n}\right) \right) & t \leq t_d \\ \frac{u(t)}{(u_{st})_o} = \frac{(T_n / t_d) \cos(\pi t_d / T_n)}{(T_n / 2t_d)^2 - 1} \sin\left(2\pi \left(\frac{t}{T_n} - \frac{t_d}{2T_n}\right)\right) & t \geq t_d \end{cases} \quad (3.8)$$

Where,  $\delta(x - vt)$  is the Dirac delta function centered at  $x = vt$ , it is a mathematical description of the traveling concentrated load. The generalized force is half cycle sine pulse:

$$\begin{aligned} \tilde{p}(t) &= \int_0^L p(x, t) \Psi(x) dx = \begin{cases} \int_0^L P_0 \delta(x - vt) \sin(\pi x / L) & 0 \leq t \leq t_d \\ 0 & t \geq t_d \end{cases} \\ &= \begin{cases} p_o \sin(\pi t / t_d) & 0 \leq t \leq t_d \\ 0 & t \geq t_d \end{cases} \\ &= \begin{cases} p_o \sin(\pi t / t_d) & 0 \leq t \leq t_d \\ 0 & t \geq t_d \end{cases} \end{aligned} \quad (3.9)$$

3. We solve the equation of motion.

$$\tilde{m} \ddot{z} + \tilde{k} z = \tilde{p}(t) \quad (3.10)$$

The following two equations are used to describe the response of single degree of freedom system to a half-cycle sine pulse. We will adopt this solution for our case.

$$\begin{aligned} \frac{u(t)}{(u_{st})_o} &= \frac{1}{1 - (T_n / 2t_d)^2} \times \left( \sin\left(\pi \frac{t}{t_d}\right) - \frac{T_n}{2t_d} \left(2\pi \frac{t}{T_n}\right) \right) & t \leq t_d \\ \frac{u(t)}{(u_{st})_o} &= \frac{(T_n / t_d) \cos(\pi t_d / T_n)}{(T_n / 2t_d)^2 - 1} \sin\left(2\pi \left(\frac{t}{T_n} - \frac{t_d}{2T_n}\right)\right) & t \geq t_d \end{aligned} \quad (3.11)$$

$$t_d = \frac{L}{V} \quad T_n = \frac{2\pi}{w_n} \quad (Z_{st})_0 = \frac{P_0}{\tilde{k}} = \frac{2P_0}{mLw_n^2}$$

The results are:

$$Z(t) = \frac{2P_0}{mL} \frac{1}{w_n^2 - (\pi v / L)^2} \left( \sin \frac{\pi v t}{L} - \frac{\pi v}{w_n L} \sin w_n t \right) \quad t \leq L / v \quad (3.12)$$

$$Z(t) = \frac{-2P_0}{mL} \frac{(2\pi v / w_n L) \cos(w_n L / 2v)}{w_n^2 - (\pi v / L)^2} \sin[w_n(t - L / 2v)] \quad t \geq L / v \quad (3.13)$$

The response given by equation (4.12) is when the moving vehicle is on the bridge span and equation (4.13) is after the moving load crossed the span.

4. We determine the deflection at mid span.

$$u(x, t) = z(t)\psi(x) = z(t) \sin \frac{\pi x}{L} \quad (3.14)$$

$$\text{At mid span} \quad x = \frac{L}{2} \quad u\left(\frac{L}{2}, t\right) = z(t) \quad (3.15)$$

Thus, the deflection at midspan is also given by (3.12) and (3.13).

5. Numerical results. For the given reinforced concrete slab bridge and vehicle speed.

For C20/25 concrete: mass per unit volume=2548.5377kg/m<sup>3</sup>

$$L = 10m \quad w = 3.66 \times 2 = 7.32m \quad \text{Speed} = 40Kmh = 11.2m / \text{sec} \quad \text{Depth} = 0.54m$$

$$m = 2548.5377 \times 10 \times 7.32 \times 0.54 = 100,738.5982 \text{ kg}$$

$$I = \frac{bh^3}{12} = \frac{7.32 \times (0.54)^3}{12} = 0.09605304 \text{ m}^4$$

$$EI = 30 \times 10^9 \frac{\text{N}}{\text{m}^2} \times 0.09605304 \text{ m}^4 = 2.8815912 \times 10^9 \text{ Nm}^2$$

$$w_n = \frac{\pi^2}{L^2} \sqrt{\frac{EI}{m}} = \frac{\pi^2}{100} \times \sqrt{\frac{2.8815912 \times 10^9 \text{ Nm}^2}{100,738.5982 \text{ kg}}} = 16.6924 \text{ rad / sec}$$

$$T_n = \frac{2\pi}{w_n} = 0.3764 \text{ sec}$$

$$\frac{\pi v}{L} = 3.5186 \text{ sec}$$

$$\frac{L}{v} = \frac{10 \text{ m}}{11.2 \text{ m / sec}} = 0.893 \text{ sec} = t_d$$

Because, the duration of the half-cycle sine pulse  $t_d = L/v$  is greater than  $T_n/2$ , the maximum response occurs when the moving tandem load is on the bridge span.

$$\begin{aligned} Z(t) &= \frac{2P_o}{mL} \frac{1}{w_n^2 - (\pi v / L)^2} \left( \sin \frac{\pi v t}{L} - \frac{\pi v}{w_n L} \sin w_n t \right) \quad t \leq L / v \\ &= \frac{2 \times 222,411.2 \text{ N}}{100,738.5982 \times 10} \times \frac{1}{278.636 - 12.381} \times (\sin 3.5186t - 0.2108 \sin 16.6924t) \\ &= \frac{444,822.4}{268,221,554.6} \times (\sin 3.5186t - 0.2108 \sin 16.6924t) \\ &= 1.6584 \times 10^{-3} (\sin 3.5186t - 0.2108 \sin 16.6924t) \end{aligned}$$

$$\begin{aligned} Z(t) &= \frac{2P_o}{mL} \frac{1}{w_n^2 - (\pi v / L)^2} \left( \sin \frac{\pi v t}{L} - \frac{\pi v}{w_n L} \sin w_n t \right) \quad t \leq L / v \\ &= \frac{2 \times 222,411.2 \text{ N}}{100,738.5982 \times 10} \times \frac{1}{278.636 - 12.381} \times (\sin 3.5186t - 0.2108 \sin 16.6924t) \\ &= \frac{444,822.4}{268,221,554.6} \times (\sin 3.5186t - 0.2108 \sin 16.6924t) \\ &= 1.6584 \times 10^{-3} (\sin 3.5186t - 0.2108 \sin 16.6924t) \end{aligned}$$

Table 3.2 The deflection at different times using equation 3.12.

$$(\sin 3.5186t - 0.2108 \sin 16.6924t)$$

Constant:            3.51861  
                               0.2108  
                               16.6924

time	$\sin(3.5186t)$	constant	$\text{Sin}(16.6924t)$	$0.2108\sin(16.6924t)$	$\sin(3.5186t)-0.2108\sin(16.6924t)$	time
0	0	0.2108	0	0	0	0
0.02	0.070314131	0.2108	0.327680991	0.069075153	0.001238978	0.02
0.04	0.140280193	0.2108	0.619178415	0.13052281	0.009757383	0.04
0.06	0.209551839	0.2108	0.842304208	0.177557727	0.031994112	0.06
0.08	0.277786161	0.2108	0.972420117	0.204986161	0.0728	0.08
0.1	0.344645385	0.2108	0.995158334	0.209779377	0.134866009	0.1
0.12	0.409798545	0.2108	0.908008032	0.191408093	0.218390452	0.12
0.14	0.472923118	0.2108	0.720592623	0.151900925	0.321022193	0.14
0.16	0.533706626	0.2108	0.453607107	0.095620378	0.438086248	0.16
0.18	0.591848178	0.2108	0.136532865	0.028781128	0.56306705	0.18
0.2	0.647059961	0.2108	-0.19561777	-0.04123622	0.688296186	0.2
0.22	0.699068666	0.2108	-0.50616767	-0.10670014	0.80576881	0.22
0.24	0.747616839	0.2108	-0.76082494	-0.1603819	0.907998736	0.24
0.26	0.792464156	0.2108	-0.93146953	-0.19635378	0.988817932	0.26
0.28	0.833388615	0.2108	-0.99925831	-0.21064365	1.044032268	0.28
0.3	0.870187632	0.2108	-0.95670585	-0.20167359	1.071861225	0.3
0.32	0.902679042	0.2108	-0.80851091	-0.1704341	1.073113143	0.32
0.34	0.930702008	0.2108	-0.57103765	-0.12037474	1.051076746	0.34
0.36	0.95411781	0.2108	-0.27050862	-0.05702322	1.011141027	0.36
0.38	0.972810535	0.2108	0.059890831	0.012624987	0.960185548	0.38
0.4	0.98668765	0.2108	0.383676946	0.0808791	0.90580855	0.4
0.42	0.995680461	0.2108	0.665096244	0.140202288	0.855478173	0.42
0.44	0.999744452	0.2108	0.873073519	0.184043898	0.815700554	0.44

## Determination of Dynamic Load Allowance Factor for Reinforced Concrete Highway Bridges

0.46	0.998859504	0.2108	0.984643267	0.207562801	0.791296703	0.46
0.48	0.993029999	0.2108	0.987485603	0.208161965	0.784868034	0.48
0.5	0.982284793	0.2108	0.881286668	0.18577523	0.796509564	0.5
0.52	0.966677079	0.2108	0.677773283	0.142874608	0.823802471	0.52
0.54	0.946284116	0.2108	0.399418037	0.084197322	0.862086794	0.54
0.56	0.921206855	0.2108	0.076957794	0.016222703	0.904984152	0.56
0.58	0.891569433	0.2108	-0.25400037	-0.05354328	0.945112711	0.58
0.6	0.85751856	0.2108	-0.55691102	-0.11739684	0.974915403	0.6
0.62	0.819222797	0.2108	-0.79832579	-0.16828708	0.987509874	0.62
0.64	0.776871715	0.2108	-0.95158692	-0.20059452	0.977466237	0.64
0.66	0.73067496	0.2108	-0.99977082	-0.21075169	0.941426649	0.66
0.68	0.680861215	0.2108	-0.93755688	-0.19763699	0.878498205	0.68
0.7	0.627677069	0.2108	-0.77181495	-0.16269859	0.790375661	0.7
0.72	0.571385794	0.2108	-0.52084679	-0.1097945	0.681180297	0.72
0.74	0.512266043	0.2108	-0.21236508	-0.04476656	0.557032603	0.74
0.76	0.450610471	0.2108	0.119566646	0.025204649	0.425405822	0.76
0.78	0.386724286	0.2108	0.438295449	0.092392681	0.294331606	0.78
0.8	0.320923737	0.2108	0.708626288	0.149378421	0.171545316	0.8
0.82	0.253534551	0.2108	0.90070838	0.189869326	0.063665224	0.82
0.84	0.184890317	0.2108	0.993331415	0.209394262	-0.024503946	0.84
0.86	0.115330838	0.2108	0.976267666	0.205797224	-0.090466386	0.86
0.88	0.045200448	0.2108	0.851401367	0.179475408	-0.13427496	0.88
0.9	0.025153693	0.2108	0.632520646	0.133335352	-0.158489045	0.9

MAX= **1.073113143**

The maximum deflection at mid span  $x = 5m$  is:

$$Z(t) = 1.6584 \times 10^{-3} m \times 1.07311 = 1.78 mm$$

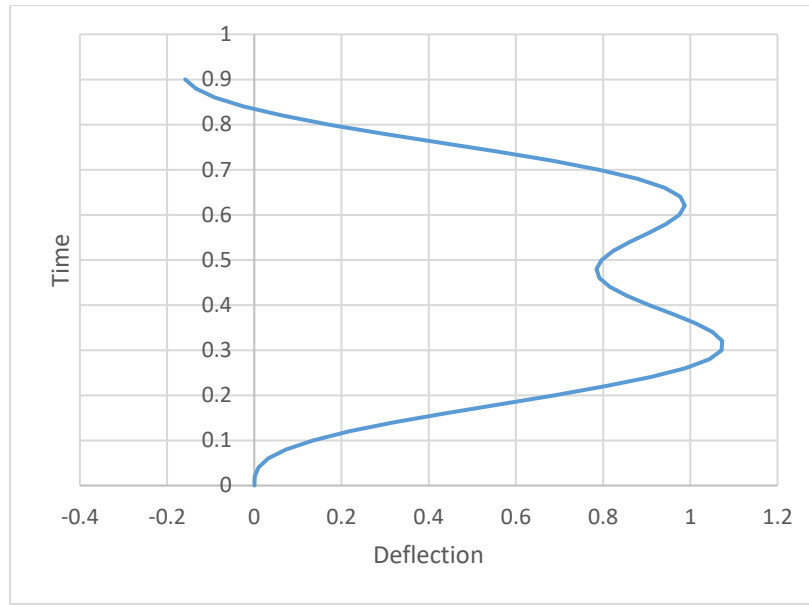


Figure 3.4 plot of deflection Vs. time

### 3.4.3 Comparison of Dynamic Analysis Results

The deflection output of both methods is shown in the table below.

Table 3.3 Dynamic deflection outputs of both methods.

CSI Bridge mid span deflection output (mm)	Analytical solution deflection output (mm)	Accuracy (%)
1.586	1.780	89.1

## 3.5 Field Investigation

### 3.5.1 General

Field investigation was undertaken in KOKA bridge to verify the dynamic deflection of the bridge and to study the effect of vehicle speed on the dynamic deflection. The results are used in three ways; firstly, the dynamic deflection for the bridge in question is determined. Secondly, the collected data is used to validate a finite element model. Thirdly, the effect of vehicle speed on DLA is determined. The field investigation was carried out on October 19, 2018.

The Koka bridge is located in Alemgena district, Modjo section that is located at 91.5km from Addis Ababa in Modjo-Zeway road segment. The bridge is reinforced concrete T-girder bridge supported by masonry abutments. It has three spans and each span length is 18.5m. The bridge was constructed in 1953. Deflection measuring tool was installed at mid span of the interior girder to measure the maximum response. Material data is not available but bridge geometric data is available.

The Sino truck vehicle loading data is obtained from the weighing station found in Modjo, Ethiopia. The figures below show the KOKA bridge cross section, installation of the deflection measuring tool and the vehicles moving with different specified speed during field investigation.

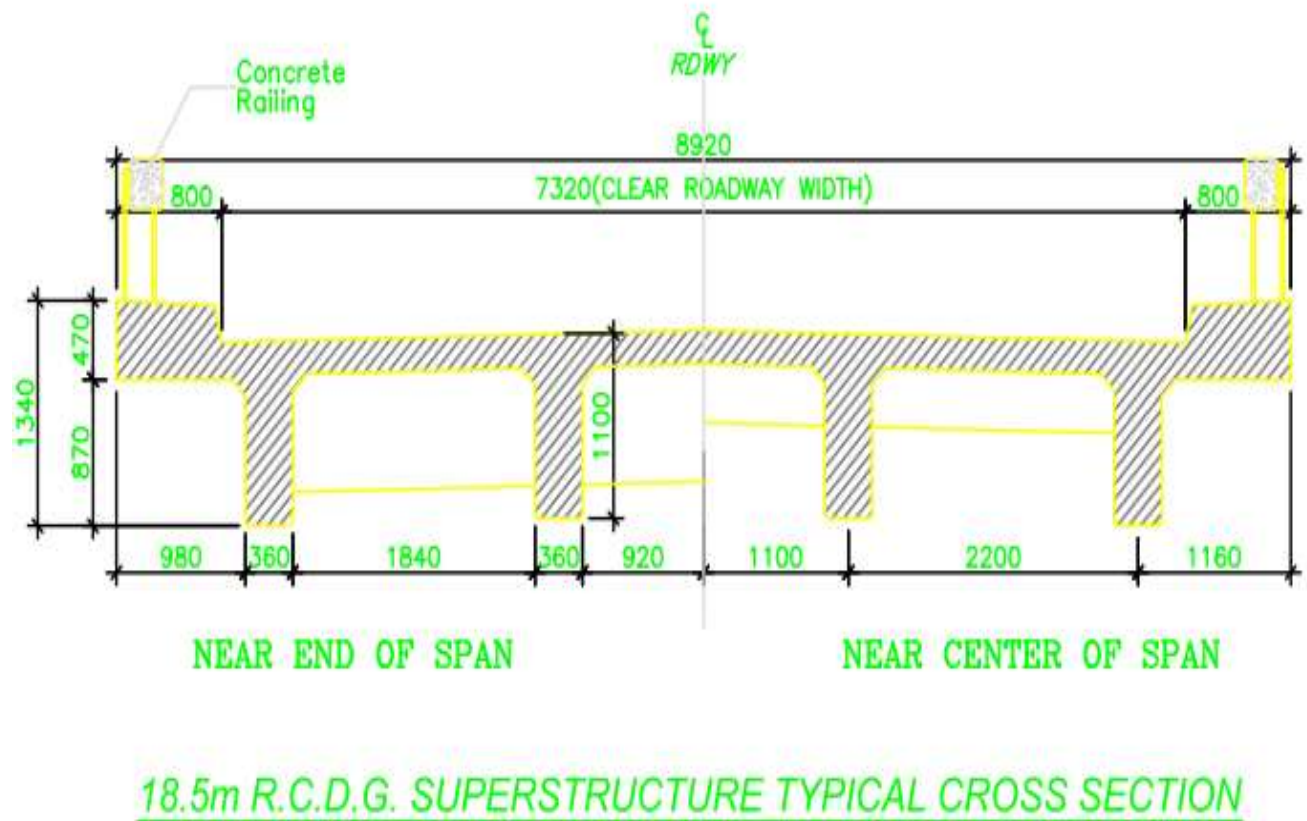


Figure 3.5 KOKA bridge superstructure cross section



Figure 3.6 Installed deflection measuring tool at mid span of the bridge



Figure 3.7 Heavy truck with multiple axle load carrying 172-ton transformer approaches and passes the bridge with a crawling speed of 4Kmh.



Figure 3.8 Sino trucks carrying full of sand material passes on the bridge with different speeds



Figure 3.9 Measured axle weight of Sino truck from weighing station.

### 3.5.2 Field Test Results

The following results are obtained during field investigation on KOKA bridge.

1. 172-ton transformer passes on the bridge with 4Kmh speed; the bridge deflects 20mm.
2. Sino Truck with gross axle load of 306 Quintal passes on the bridge with the speed of 40Kmh; the bridge deflects 9mm.
3. Sino Truck with gross axle load of 308 Quintal passes on the bridge with the speed of 60Kmh; the bridge deflects 7mm.
4. Sino Truck with unknown gross axle load passes on the bridge with the speed of 50Kmh; the bridge deflects 5mm. Even though, the axle load of the Sino truck is not known the loading condition is almost the same as the above two Sino trucks; all three of them carry full of sand material as shown in photograph 5.3.
5. Scania with unknown gross axle load passes on the bridge with the speed of 30kmh; the bridge deflects 12mm.

Table 3.4 Effect of Sino truck speed on the dynamic deflection of KOKA bridge.

Sino truck speed (KMH)	Measured deflection from the site(mm)
40	9
50	5
60	7

### 3.5.3 Dynamic Deflection of KOKA Bridge Using CSI Bridge

The bridge cross sectional data is obtained from Ethiopian Road Authority, ERA. However, no information was available on its material property of the bridge. The bridge is of concrete construction. Following back analysis, various flexural stiffness (EI) were assumed and the bridge response is compared to the measured site dynamic deflection.

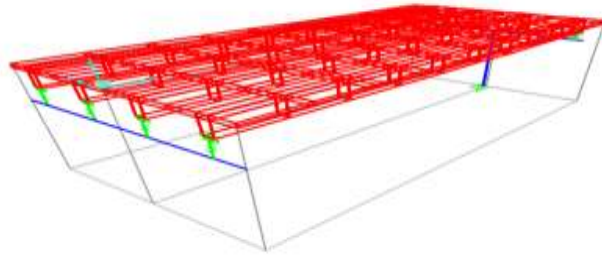


Figure 3.10 KOKA bridge model

### 3.5.4 Comparison of Field Investigation Results with CSI Bridge

The table below shows the experimental and the CSI bridge 20 analysis output.

Table 3.5 Deflection obtained from CSI Bridge and field experiment.

Speed (KMH)	Mid span deflection from field investigation( $\Delta$ )	Mid span deflection using CSI Bridge
40	9	8.979
60	7.4	7.762

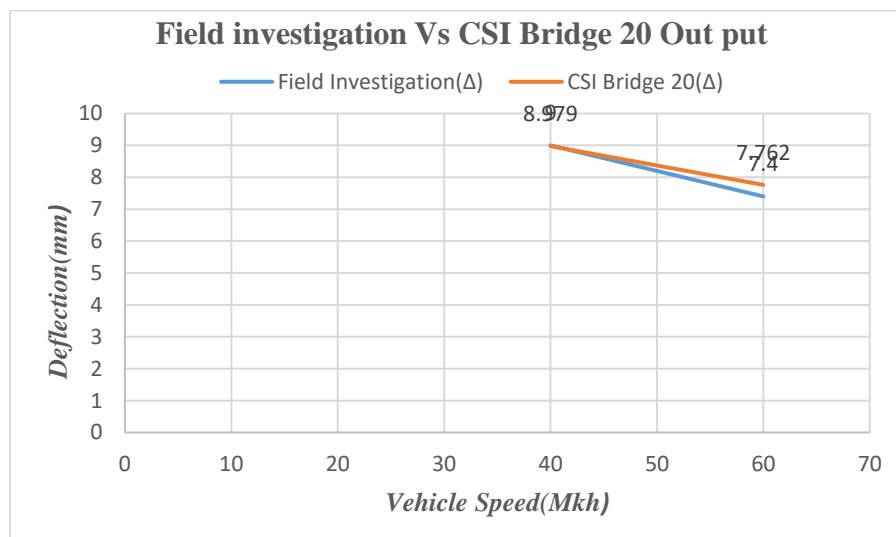


Figure 3.11 Field investigation vs CSI Bridge out put

## **4. MODELLING AND ANALYSIS FOR THE DETERMINATION OF DYNAMIC LOAD ALLOWANCE FACTOR**

### **4.1 General**

In this research, CSI Bridge 20.1.0 an integrated 3D bridge analysis and design software is used. The software product is licensed to computers and structures, Inc. Modelling, analysis, and design of bridges have been integrated into CSI Bridge 20.1.0. The presence of all these tasks in the software makes it preferable for this research. In using the CSI Bridge 20.1.0 it is easy to define complex bridge geometries, boundary conditions and load cases. The bridge models are defined parametrically, using terms familiar to bridge engineers, such as layout lines, lanes, spans, bearings, abutments, bents, hinges and diaphragms. The steps for modelling and analysis of the reinforced concrete bridges used in this research is given below.

Step 1. Define the layout line and lane data of the bridge.

Step 2. Define the material property.

Step 3. Define superstructure bridge geometric data.

Step 4. Define the substructure components.

Step 5. Define the vehicle loading data.

Step 6. Assign the vehicle load to a given lanes.

Step 7. Select the analysis type and run the analysis to get the bridge structure response.

The subsequent sub chapters give background information for the steps mentioned above during the modelling and analysis stage.

### **4.2 Material Property**

#### **4.2.1 Concrete**

The concrete compressive strength is denoted by concrete strength classes which relates to the characteristic (5%) cylindrical strength  $f_{ck}$ , or the cube strength  $f_{ck,cube}$ . The strength classes in the code is based on the characteristic strength  $f_{ck}$  determined at 28 days [14]. In this research, a

concrete strength class of C20/25 is used throughout the analysis of reinforced concrete bridges. The material property of the bridge is given in Appendix A.2.

### 4.3. Bridge Dimensioning

#### 4.3.1 Roadway Width

The Ethiopian Bridge Design Manual 2013 in chapter 2 section 2.3.3.3, puts the bridge width according to the roadway or carriageway width as determined according to the prevailing version of the ERA geometric design manual. If the ERA geometric design manual not stated the manual recommends to use 4.2m and above width for one lane bridge and 7.0m and above for two lane bridge. The manual puts the bridge widths according to their application in the table as shown below.

Table 4.1 Bridge widths according to their application [8].

Application	Width (m)
Two-lane in "urban" area	10.30
Two-lane in "rural" area	7.30
Single lane	4.20
Pedestrian overpass	3.0

The dimensions of 7.30m for two-lane bridge are based on trucks with widths of 2.4m meeting, providing 0.7m clearance between vehicles and at the sides, the greater clearance allowing a higher average speed. In this thesis a width of 7.32m two-lane rural area bridge is selected and a pedestrian walkway of 0.8m in both sides is added, total of 8.92m width is used throughout the research for both Slab and Girder highway bridges.

#### 4.3.2 Depth Determination

##### 3.3.2.1 Depth for Slab Bridges

The minimum required depth for slab bridges with the main reinforcement parallel to the traffic

$$\text{is: } D=1.2 \frac{(S + 3000)}{30} , \quad (4.1)$$

Where, S is center to center spacing of the bridge.

The table below shows the recommended depth used for the different bridge span lengths; span length of 5m to 15m.

Table 4.2 Depth of slab bridge for different span lengths.

Span length(m)	S (mm)	D(mm)
5	5500	340
10	10500	540
15	15500	740

#### 4.3.2.2 Depth for T-girder Bridges

- Unless approved by Ethiopian Road Authority (ERA) the depth of a concrete deck, excluding any provision for grinding, grooving, and sacrificial surface, should not be less than 185mm [8].
- The minimum thickness of the web,  $b_{min} = 200\text{mm}$  without prestressing duct, and
- Total depth,  $D_w$  for simple span T-beams  $D_w = 0.07L$  [7].

The table below shows the recommended depth used for the different bridge span length of 20m to 25m, thickness of the slab and web thickness.

Table 4.3 slab thickness, web thickness and total depth for different span lengths of T-girder bridges.

Span Length(m)	Cs (m)	B (mm)	L (mm)	D (mm)	$t_s(\text{mm})$
12	12	360	12000	840	200
20	20	360	20000	1400	200
25	25	360	25000	1750	200

#### 4.3.2.3 Depth for Box Girder Bridges

- Unless approved by Ethiopian Road Authority (ERA) the depth of a concrete deck, excluding any provision for grinding, grooving, and sacrificial surface, should not be less than 185mm [8].

- The minimum thickness of the web,  $b_{\min} = 200\text{mm}$  without prestressing duct,
- Total depth,  $D_w$  for simple span T-beams  $D_w = 0.06L$ , and
- The minimum recommended thickness of the bottom slab,  $t_{sb, \min} = 140\text{mm}$  [7].

Table 4.4 Top and bottom slab thickness, web thickness and total depth for different span lengths of box-girder bridges.

Span Length(m)	Cs (m)	B (mm)	L (mm)	D (mm)	$t_s$ top(mm)	$t_s$ bottom(mm)
25	25	250	25000	1500	200	150
30	30	250	30000	1800	200	150
35	35	250	35000	2100	200	150
40	40	250	40000	2400	200	150

#### 4.5 Loading Conditions

Truck loadings are the primary design parameters for highway bridges. The American Association of State and Highway Officials (AASHTO), founded in 1914 as AASHO, developed the concept of a train of trucks in the 1935 that imitated the railroad industry's standards. Nevertheless, as the weight of the trucks increases, the bridges were overstressed.

New concept was developed in 1944 in AASHTO that is the concept of hypothetical trucks, called the H (with two-axles) and the HS (with three-axles) classes of trucks. These trucks were fictitious trucks, used only for design and they did not look like any real truck on the road. New much heavier trucks were included in 1944 these are H15-44(133.45KN), the H20-44(180KN), HS15-44(240KN) and the HS20-44(320.27KN). Similar standard exists for Canada (the Ontario Highway bridge design code, OHBDC) or the United Kingdom, the BS5400 code. The rear axle spacing of the HS20-44 truck is variable, that ranges from 4.267m to 9.144m, this variation is to induce maximum positive moment in the span. For simply supported span bridge the spacing of the axles will be 4.267m[15]. CSI Bridge 20 offers to add our own vehicle live loads and/or to use pre-defined vehicles on different country codes.

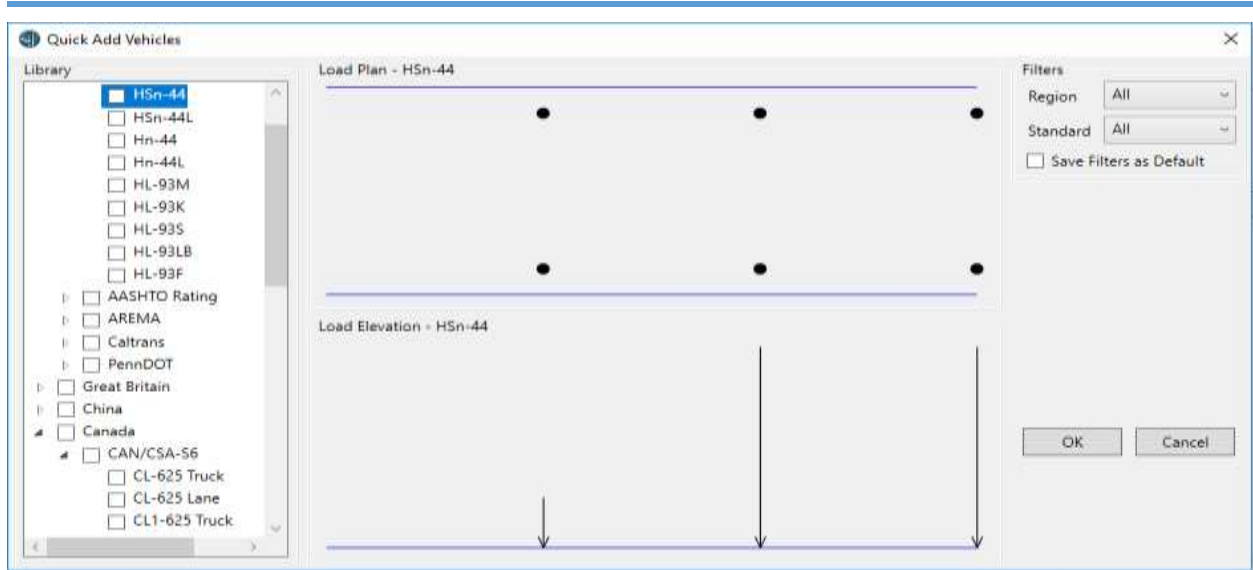


Figure 4.1 Vehicle live loads in different codes

According to AASHTO LRFD Bridge Design Specifications, Fifth Edition, 2010, section 3.6.1.2.1 modification to design truck, design tandem, and/or the design lane load can be done under the following conditions.

- ✓ The legal load of a given jurisdiction is significantly greater than typical;
- ✓ The roadway is expected to carry unusually high percentages of truck traffic;
- ✓ Flow control, such as stop sign, traffic signal, or toll booth, causes trucks to collect on certain areas of a bridge or to not be interrupted by light traffic; or
- ✓ Special industrial loads are common due to the location of the bridge.



Figure 4.2 Measured axle load and spacing of Sino truck

## 4.6 Vehicle Speed

The selected vehicular loadings tandem load for Slab bridges and Sino truck load for T-girder and Box-girder bridges are allowed to move in five different velocities: 20, 40, 60, 80, 100 Km/h.

## 4.7 Analysis

Moving load analysis can be used to determine the response of bridge structures due to weight of vehicle live loads. Time history analysis is a step-by-step analysis of the dynamical response of the structure to arbitrary loading, in our case a moving vehicle. The dynamic equilibrium equation to be solved is given by:

$$Ku(t) + C \dot{u}(t) + M \ddot{u}(t) = r(t) \quad (4.2)$$

Where, K is the stiffness matrix, C is the damping matrix, M is the diagonal mass matrix;  $u$ ,  $\dot{u}$  and  $\ddot{u}$  are the displacements, velocities, and accelerations of the structure;  $r$  is the applied load [16].

## 4.8 Determination of Dynamic Load Allowance

Considering dynamic effect resulting from the movement of vehicles is very important as tried to be shown in the previous chapters. To account for such a dynamic effect, it is required that the static live (vehicular) load be increased by a dynamic load allowance factor [1]. The basic definition of dynamic load allowance factor is the ratio of maximum dynamic response to maximum static response.

The dynamic amplification factor (DAF) of highway bridges is defined as the maximum total (dynamic plus static) load effect divided by the maximum static load effect [11]. DAF minus one gives the same result as the ratio of dynamic over static response. In this research, the former definition of dynamic load allowance factor to determine the dynamic load allowance factor is used.

$$DLA = \frac{\text{Maximum dynamic response}}{\text{Maximum static response}} \quad (4.3)$$

According to equation 4.3 dynamic load allowance factor is calculated for Slab and girder bridges; deflection at mid span is considered as the structure response for computation of the dynamic load

allowance factor. The values given below are the static and dynamic deflection of the 10m slab bridge.

$$DLA = \frac{\text{Maximum dynamic response}}{\text{Maximum static response}} = \frac{2.108\text{mm}}{5.338\text{mm}} = \underline{\underline{0.394}}$$

Computed dynamic load allowance factors is presented in the table below for Slab and Girder bridges.

Table 4.5 Dynamic load allowance factors for Slab bridges.

Span Length (m)	Speed (kmh)	Static deflection at mid span (mm)	Dynamic deflection at mid span (mm)	Dynamic allowance factor (DLA)
5	20	2.934	1.521	0.518
5	40	2.934	1.607	0.547
5	60	2.934	1.334	0.454
5	80	2.934	1.639	0.558
5	100	2.934	1.498	0.510
10	20	5.338	2.108	0.394
10	40	5.338	2.145	0.401
10	60	5.338	2.116	0.396
10	80	5.338	2.133	0.399
10	100	5.338	2.134	0.399
15	20	6.611	2.245	0.339
15	40	6.611	2.184	0.330
15	60	6.611	2.231	0.337
15	80	6.611	2.381	0.360
15	100	6.611	2.285	0.345

Table 4.6 Dynamic load allowance factors for T-girder bridges.

<b>Span Length (m)</b>	<b>Speed (kmh)</b>	<b>Static deflection at mid span (mm)</b>	<b>Dynamic deflection at mid span (mm)</b>	<b>Dynamic allowance factor (DLA)</b>
<b>12</b>	<b>20</b>	<b>5.284</b>	<b>2.477</b>	<b>0.468</b>
<b>12</b>	<b>40</b>	<b>5.284</b>	<b>2.498</b>	<b>0.472</b>
<b>12</b>	<b>60</b>	<b>5.284</b>	<b>2.458</b>	<b>0.465</b>
<b>12</b>	<b>80</b>	<b>5.284</b>	<b>2.508</b>	<b>0.474</b>
<b>12</b>	<b>100</b>	<b>5.284</b>	<b>2.637</b>	<b>0.499</b>
<b>20</b>	<b>20</b>	<b>6.652</b>	<b>2.694</b>	<b>0.405</b>
<b>20</b>	<b>40</b>	<b>6.652</b>	<b>2.712</b>	<b>0.408</b>
<b>20</b>	<b>60</b>	<b>6.652</b>	<b>2.785</b>	<b>0.419</b>
<b>20</b>	<b>80</b>	<b>6.652</b>	<b>2.865</b>	<b>0.431</b>
<b>20</b>	<b>100</b>	<b>6.652</b>	<b>2.799</b>	<b>0.421</b>
<b>25</b>	<b>20</b>	<b>7.498</b>	<b>2.886</b>	<b>0.385</b>
<b>25</b>	<b>40</b>	<b>7.498</b>	<b>2.870</b>	<b>0.383</b>
<b>25</b>	<b>60</b>	<b>7.498</b>	<b>2.987</b>	<b>0.398</b>
<b>25</b>	<b>80</b>	<b>7.498</b>	<b>2.988</b>	<b>0.399</b>
<b>25</b>	<b>100</b>	<b>7.498</b>	<b>2.910</b>	<b>0.388</b>

Table 4.7 Dynamic load allowance factors for Box-girder bridges.

<b>Span Length (m)</b>	<b>Speed (kmh)</b>	<b>Static deflection at mid span (mm)</b>	<b>Dynamic deflection at mid span (mm)</b>	<b>Dynamic allowance factor (DLA)</b>
<b>25</b>	<b>20</b>	<b>9.795</b>	<b>4.067</b>	<b>0.415</b>
<b>25</b>	<b>40</b>	<b>9.795</b>	<b>4.191</b>	<b>0.427</b>
<b>25</b>	<b>60</b>	<b>9.795</b>	<b>4.362</b>	<b>0.445</b>
<b>25</b>	<b>80</b>	<b>9.795</b>	<b>4.086</b>	<b>0.417</b>
<b>25</b>	<b>100</b>	<b>9.795</b>	<b>3.751</b>	<b>0.382</b>
<b>30</b>	<b>20</b>	<b>11.300</b>	<b>4.224</b>	<b>0.374</b>
<b>30</b>	<b>40</b>	<b>11.300</b>	<b>4.500</b>	<b>0.398</b>
<b>30</b>	<b>60</b>	<b>11.300</b>	<b>4.424</b>	<b>0.392</b>
<b>30</b>	<b>80</b>	<b>11.300</b>	<b>4.200</b>	<b>0.372</b>
<b>30</b>	<b>100</b>	<b>11.300</b>	<b>4.080</b>	<b>0.361</b>
<b>35</b>	<b>20</b>	<b>12.900</b>	<b>4.216</b>	<b>0.327</b>
<b>35</b>	<b>40</b>	<b>12.900</b>	<b>4.721</b>	<b>0.366</b>
<b>35</b>	<b>60</b>	<b>12.900</b>	<b>4.447</b>	<b>0.345</b>
<b>35</b>	<b>80</b>	<b>12.900</b>	<b>4.355</b>	<b>0.338</b>
<b>35</b>	<b>100</b>	<b>12.900</b>	<b>4.524</b>	<b>0.351</b>
<b>40</b>	<b>20</b>	<b>14.600</b>	<b>4.570</b>	<b>0.313</b>
<b>40</b>	<b>40</b>	<b>14.600</b>	<b>4.974</b>	<b>0.340</b>
<b>40</b>	<b>60</b>	<b>14.600</b>	<b>4.616</b>	<b>0.316</b>
<b>40</b>	<b>80</b>	<b>14.600</b>	<b>4.598</b>	<b>0.314</b>
<b>40</b>	<b>100</b>	<b>14.600</b>	<b>4.916</b>	<b>0.336</b>

## 5. DEVELOPMENT OF DYNAMIC LOAD ALLOWANCE FORMULA USING REGRESSION ANALYSIS

### 5.1 Introduction About Regression Analysis

We deal with datasets which are correlated and in which one or more variables classed as an independent variable and the other variable called a dependent variable. As the case of the dynamic load allowance factor depends on the bridge span length and vehicle speed. We develop a correlation formula that best exhibits the relationship of these variables using multiple linear regression analysis.

Multiple linear regression is a useful extension of linear regression in the case where the dependent variable; dynamic load allowance factor is a function of two or more independent variables in our case the bridge span length and vehicle speed [17]. As an example, Y might be a linear function of X1 and X2 as in

$$Y = a_0 + a_1x_1 + a_2x_2 + e \quad (5.1)$$

The coefficients yielding the minimum sum of squares of the residuals are obtained by setting the partial derivatives equal to zero and expressing the result in matrix form as:

$$\begin{pmatrix} n & \sum x_{1i} & \sum x_{2i} \\ \sum x_{1i} & \sum x_{1i}^2 & \sum x_{1i}x_{2i} \\ \sum x_{2i} & \sum x_{1i}x_{2i} & \sum x_{2i}^2 \end{pmatrix} \begin{Bmatrix} a_0 \\ a_1 \\ a_2 \end{Bmatrix} = \begin{Bmatrix} \sum y_i \\ \sum x_{1i}y_i \\ \sum x_{2i}y_i \end{Bmatrix} \quad (5.2)$$

$$S_r = \sum (y_i - y_{cal})^2 \quad (5.3)$$

$S_r$  is sum of squared differences; the best fit curve is the one for which  $S_r$  is the minimum.

$$S_t = \sum (y_i - \bar{y})^2 \quad (5.4)$$

$$r = \sqrt{\frac{S_t - S_r}{S_t}} \quad (5.5)$$

$r$  - correlation coefficient. The values of  $r$  that explains the correlation degree is given below.

$r = 0$  implies no relation

$r =$  between 0.1 to 0.2 implies low, probably meaningless relation

$r =$  between 0.4 to 0.6 implies moderate correlation

$r =$  between 0.6 to 0.8 implies high correlation

$r =$  between 0.8 to 1 implies very high correlation

## 5.2 Regression Analysis for Slab Bridges

The input data for regression analysis for the slab bridges is shown in table below.

Table 5.1 Input data of slab bridges for regression analysis.

Span Length(m)	Speed (Kmh)	Dynamic load Allowance Factor (DLA)
5	20	0.518
5	40	0.547
5	60	0.454
5	80	0.558
5	100	0.510
10	20	0.394
10	40	0.401
10	60	0.396
10	80	0.399
10	100	0.399
15	20	0.339
15	40	0.330
15	60	0.337
15	80	0.360
15	100	0.345

For multiple linear regression analysis let;

$X_1$ =Span Length in meter(m),  $X_2$ =Speed in Kilometer per hour (Kmh) and  $Y$ = Dynamic Load Allowance (DLA) Factor. The outputs and computations of the regression analysis is shown in the following figures and tables below.

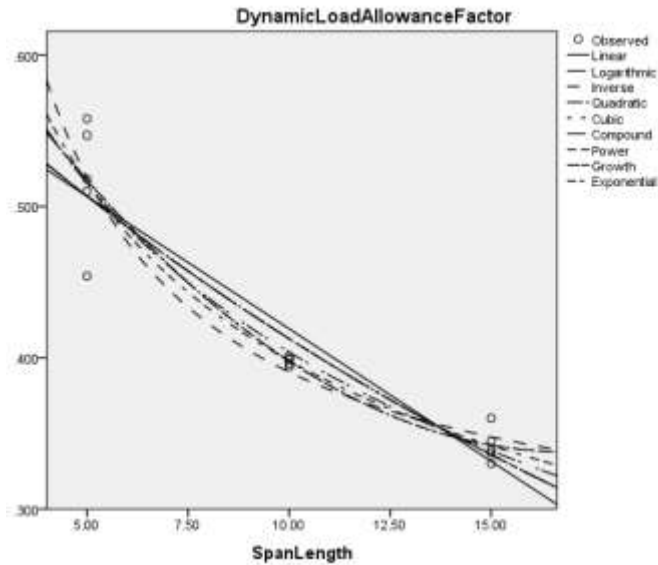


Figure 5.1 Effect of span length on the dynamic load allowance factor for slab bridges

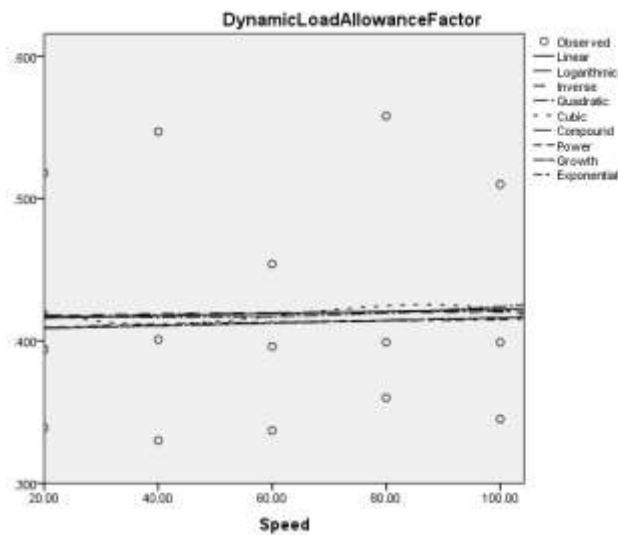


Figure 5.2 Effect of speed on dynamic load allowance factor for slab bridges

Y	X1	X2	(X1) <sup>2</sup>	(X2) <sup>2</sup>	X1*X2	X1*Y	X2*Y
0.518	5	20	25	400	100	2.59	10.36
0.547	5	40	25	1600	200	2.735	21.88
0.454	5	60	25	3600	300	2.27	27.24
0.558	5	80	25	6400	400	2.79	44.64
0.510	5	100	25	10000	500	2.55	51

## Determination of Dynamic Load Allowance Factor for Reinforced Concrete Highway Bridges

0.394	10	20	100	400	200	3.94	7.88	
0.401	10	40	100	1600	400	4.01	16.04	
0.396	10	60	100	3600	600	3.96	23.76	
0.399	10	80	100	6400	800	3.99	31.92	
0.399	10	100	100	10000	1000	3.99	39.9	
0.339	15	20	225	400	300	5.085	6.78	
0.330	15	40	225	1600	600	4.95	13.2	
0.337	15	60	225	3600	900	5.055	20.22	
0.36	15	80	225	6400	1200	5.4	28.8	
0.345	15	100	225	10000	1500	5.175	34.5	
<b>SUM=</b>	<b>6.287</b>	<b>150</b>	<b>900</b>	<b>1750</b>	<b>66000</b>	<b>9000</b>	<b>58.49</b>	<b>378.12</b>

Using equation 5.2 expressing the result in matrix form for slab bridges is:

$$\begin{array}{ccccccc}
 15 & 150 & 900 & a_0 & 6.287 \\
 150 & 1,750 & 9,000 & a_1 & = & 58.49 \\
 900 & 9,000 & 66,000 & a_2 & 378.12
 \end{array}$$

$$\begin{array}{ccc}
 \mathbf{A} & \mathbf{a}_i & \mathbf{b}
 \end{array}$$

$$\mathbf{A} \times \mathbf{a}_i = \mathbf{b}$$

$$\mathbf{a}_i = \mathbf{A}^{-1} \times \mathbf{b} \quad , \quad \mathbf{A}^{-1} \text{ is inverse of } \mathbf{A}.$$

$$\mathbf{A}^{-1} = \begin{array}{ccc}
 0.7666667 & -0.04 & -0.005 \\
 -0.4 & 0.004 & 0 \\
 -0.005 & 0 & 0.0000833
 \end{array}$$

$$\mathbf{a}_i = \begin{array}{ccc}
 0.7666667 & -0.04 & -0.005 \\
 -0.4 & 0.004 & 0 \\
 -0.005 & 0 & 0.0000833
 \end{array} \times \begin{array}{c} 6.287 \\ 58.49 \\ 378.12 \end{array} = \begin{array}{c} \mathbf{0.5898333} \\ \mathbf{-0.01752} \\ \mathbf{0.000075} \end{array}$$

Y-Observed	Y-Calculated	Sr=(Yi-Ycal) <sup>2</sup>	St=(Yi-Ymean) <sup>2</sup>
0.468	0.4645638	1.18075E-05	0.001626778
0.472	0.4692638	7.48679E-06	0.001965444
0.465	0.4739638	8.03497E-05	0.001393778
0.474	0.4786638	2.1751E-05	0.002146778
0.499	0.4833638	0.000244491	0.005088444
0.405	0.4116518	4.42464E-05	0.000513778
0.408	0.4163518	6.97526E-05	0.000386778
0.419	0.4210518	4.20988E-06	7.51111E-05
0.431	0.4257518	2.75436E-05	1.11111E-05
0.421	0.4304518	8.93365E-05	4.44444E-05
0.385	0.3785818	4.11933E-05	0.001820444
0.383	0.3832818	7.94112E-08	0.001995111
0.398	0.3879818	0.000100364	0.000880111
0.399	0.3926818	3.99197E-05	0.000821778
0.388	0.3973818	8.80182E-05	0.001573444
	SUM=	0.00087055	0.020343333

$$\text{Correlation coefficient, } r = \sqrt{\frac{St - Sr}{St}} = \sqrt{\frac{0.00087055 - 0.020343333}{0.020343333}} = \underline{0.938012}$$

$r = 0.938012$  is between 0.8 to 1 implies very high correlation.

$$\mathbf{DLA = 0.5898333 - 0.01752 \times L + 0.000075 \times S}$$

Dynamic load allowance for reinforced concrete Slab bridges:

$$DLA = 0.589 - \frac{1752}{100,000} L + \frac{7.5}{100,000} S \quad 5 \leq L \leq 15 \quad (5.6)$$

where,  $L$  is in meter and  $S$  is in kilometer per hour.

### 5.3 Regression Analysis for T-girder Bridges

Similar procedure has been implemented for T-girder bridges and the following results obtained.

Table 5.2 Input data of T-girder bridges for regression analysis.

Span Length(m)	Speed (KMH)	Dynamic Allowance Factor (DLA)
12	20	0.468
12	40	0.472
12	60	0.465
12	80	0.474
12	100	0.499
20	20	0.405
20	40	0.408
20	60	0.419
20	80	0.431
20	100	0.421
25	20	0.385
25	40	0.383
25	60	0.398
25	80	0.399
25	100	0.388

The matrix form for T-girder bridges is shown below:

$$\begin{array}{cccccc}
 15 & 285 & 900 & a_0 & 6.415 \\
 285 & 5,845 & 17,100 & a_1 & = & 119.041 \\
 900 & 17,100 & 66,000 & a_2 & 387.72
 \end{array}$$

Using multiple linear regression analysis, correlation coefficient of  $r = 0.97837$  is obtained; which indicates very high correlation.

$$\mathbf{DLA=0.5392318-0.006614 \times L+0.000235 \times S}$$

Dynamic load allowance for reinforced concrete T-girder bridges:

$$DLA = 0.539 - \frac{6,614}{1,000,000} L + \frac{235}{1,000,000} S \quad 12 \leq L \leq 25 \quad (5.7)$$

where,  $L$  is in meter and  $S$  is in kilometer per hour.

### 5.4 Regression Analysis for Box-Girder Bridges

Similar procedure has been implemented for Box-girder bridges and the following results obtained.

Table 5.3 Input data of Box-girder bridges for regression analysis.

Span Length(m)	Speed (KMH)	Dynamic Allowance Factor (DLA)
25	20	0.415
25	40	0.427
25	60	0.445
25	80	0.417
25	100	0.382
30	20	0.374
30	40	0.398
30	60	0.392
30	80	0.372
30	100	0.361
35	20	0.327
35	40	0.366
35	60	0.345
35	80	0.338
35	100	0.351
40	20	0.313
40	40	0.340
40	60	0.316
40	80	0.314
40	100	0.336

The matrix form:

$$\begin{matrix}
 & 20 & 650 & 1,200 & a_0 & 7.329 \\
 & 650 & 21,750 & 39,000 & a_1 & = & 234.265 \\
 & 1,200 & 39,000 & 88,000 & a_2 & & 437.98
 \end{matrix}$$

Using multiple linear regression analysis, correlation coefficient of  $r = 0.83452$  is obtained; which indicates very high correlation.

$$DLA = 0.57728 - 0.006284 \times L - 0.00011 \times S$$

Dynamic load allowance for reinforced concrete Box-girder bridges:

$$DLA = 0.577 - \frac{6,284}{1,000,000} L - \frac{11}{100,000} S \quad 25 \leq L \leq 40 \quad (5.8)$$

where,  $L$  is in meter and  $S$  is in kilometer per hour.

Summary of results: dynamic load allowance formulas:

Bridge types	DLA formula
Slab Bridges	$DLA = 0.589 - \frac{1752}{100,000} L + \frac{7.5}{100,000} S$
T-girder Bridges	$DLA = 0.539 - \frac{6,614}{1,000,000} L + \frac{235}{1,000,000} S$
Box-girder Bridges	$DLA = 0.577 - \frac{6,284}{1,000,000} L - \frac{11}{100,000} S$

## **6. CONCLUSIONS AND RECOMMENDATION**

### **6.1 Conclusion**

Accurate determination of dynamic load allowance factor will lead to safe and economical design of new bridges. The primary objective of this research is to assess the different bridge code provisions for the DLA factor and to develop new simple DLA formula for Slab and Girder highway bridges. To do that different parameters like loading conditions, vehicle speeds and bridge span lengths are considered. Using CSI Bridge static and dynamic analysis was conducted to determine the dynamic load allowance factor. In these regards, the following conclusions are made.

1. From the research, higher values from the specified 33% is obtained for span lengths up to 35m for slab, T-girder and Box-girder bridges. The formulas can be used during designing of new bridges. More comprehensive analysis should be done before the proposed formulas put into general use.
2. Loading condition, axle spacing and bridge span length has major effect on the dynamic load allowance factor.
3. For speed range of 20Kmh to 100Kmh, an increase of vehicle speed does not fundamentally guarantee an increase in DLA factor. The proposed formulas can be used for provision of speed limit.

### **6.2 Recommendation**

This study has mainly focused on the determination of new DLA formula by considering different influential parameters for reinforced concrete slab and Girder highway bridges. From the research findings, the following recommendations are drawn:

1. The developed formulas are easy to apply; bridge designers can use of the formulas for reinforced concrete slab and Girder highway bridge design.
2. One can extend this study by adding additional parameters like road way roughness, damping and bridge material like steel.
3. One can make future study on determination of dynamic load allowance factor for fatigue and fracture limit states.

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## APPENDIX A. FIGURES FOR MODELLING AND ANALYSIS USING CSI BRIDGE

### Appendix A.1 Bridge layout and lane data

**Bridge Lane Data**

General  
 Lane Name: R lane  
 Coordinate System: GLOBAL  
 Units: KN, m, C

Maximum Lane Load Discretization Lengths  
 Along Lane: 3  
 Across Lane: 3

Additional Lane Load Discretization Parameters Along Lane  
 Discretization Length Not Greater Than 1/ 4 of Span Length  
 Discretization Length Not Greater Than 1/ 10 of Lane Length

Bridge Layout Line	Station m	Centerline Offset m	Lane Width m	Radius m
CL	0.	1.83	3.66	0.
CL	0.	1.83	3.66	0.
CL	10.	1.83	3.66	0.

Lane type  
 Fixed Lane  
 Floating Lane Set  
 1 Fixed Lane  
 Auto  
 Floating Lane Width:   
 Define Floating Lanes:

Plan View (X-Y Projection)  
 Layout Line:   
 Station:   
 Bearing:   
 Radius:   
 Grade:   
 X: 9.93  
 Y: 0.7055  
 Z:   
 Snap To Layout Line  
 Snap To Lane

Lane Edge Type  
 Left Edge: Interior  
 Right Edge: Exterior

Objects Loaded By Lane  
 Program Determined  
 Group

OK Cancel

### Appendix A. 2 Material data

**Material Property Data**

General Data  
 Material Name and Display Color: C20/25  
 Material Type: Concrete  
 Material Notes:  Modify/Show Notes...

Weight and Mass  
 Weight per Unit Volume: 24.9926  
 Mass per Unit Volume: 2.5485  
 Units: KN, m, C

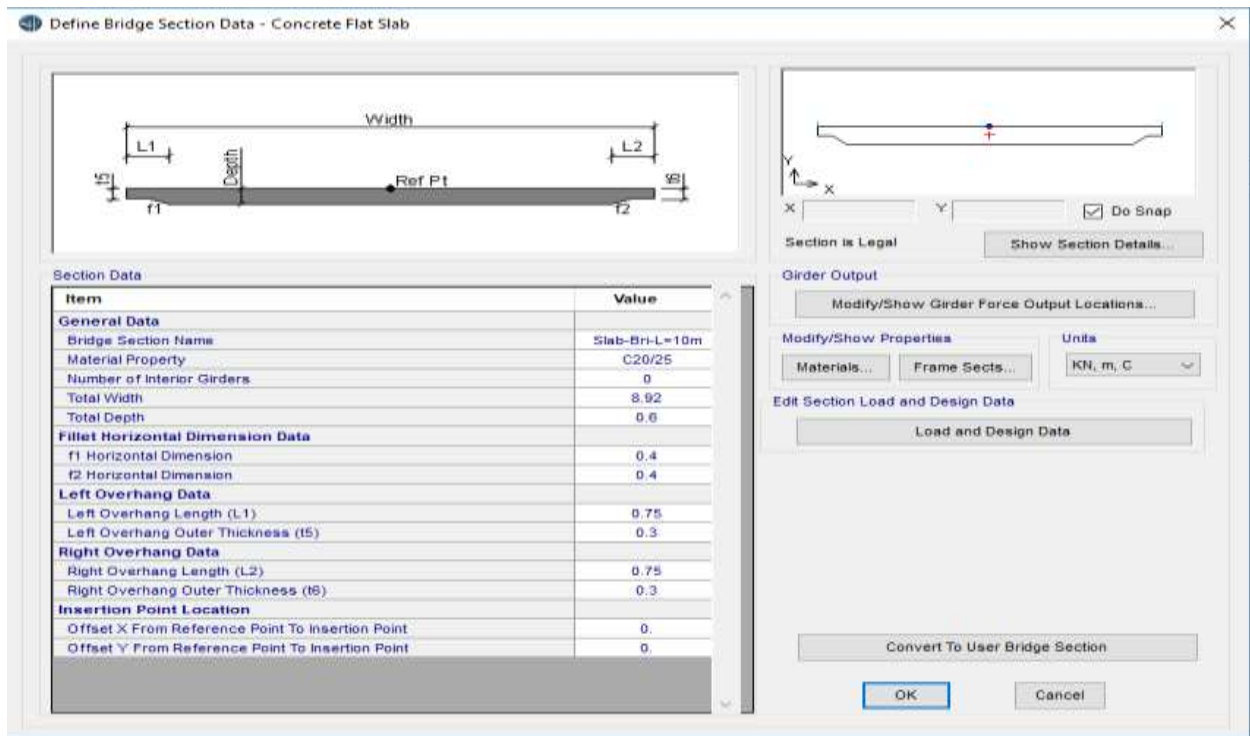
Isotropic Property Data  
 Modulus Of Elasticity, E: 30000000.  
 Poisson, U: 0.2  
 Coefficient Of Thermal Expansion, A: 1.000E-05  
 Shear Modulus, G: 12500000.

Other Properties For Concrete Materials  
 Specified Concrete Compressive Strength, Fc: 20000.  
 Expected Concrete Compressive Strength: 20000.  
 Lightweight Concrete  
 Shear Strength Reduction Factor:

Switch To Advanced Property Display

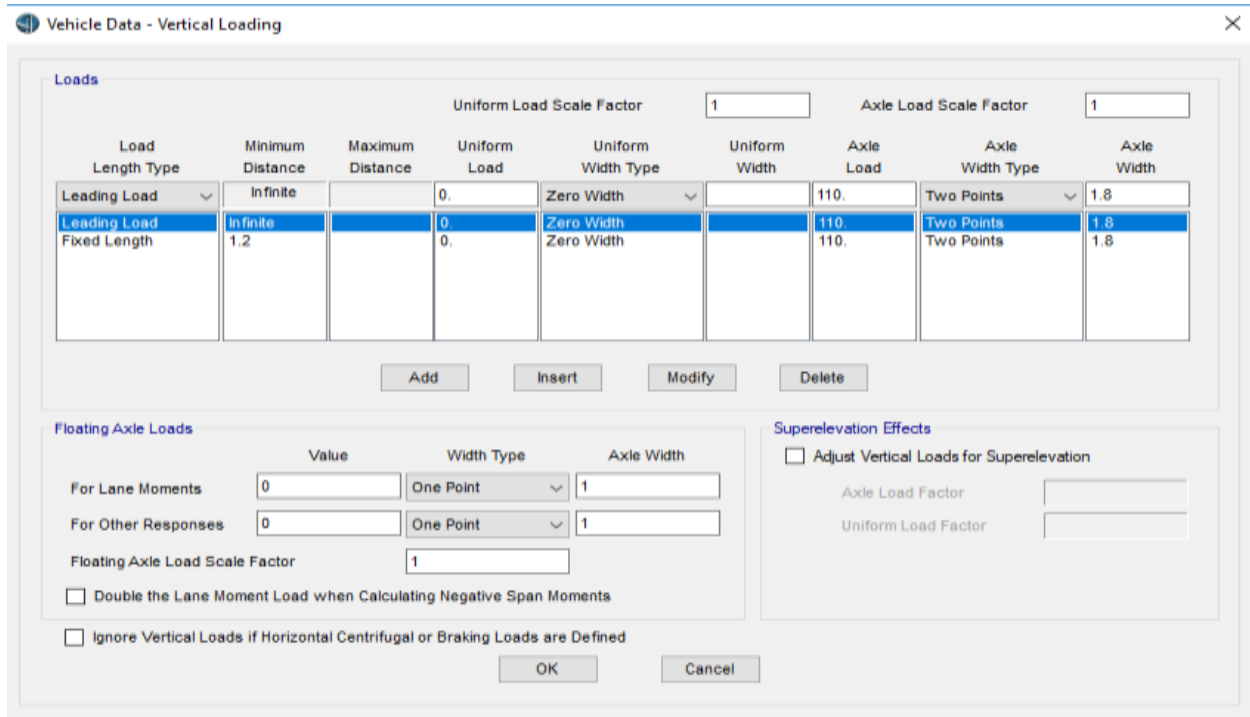
OK Cancel

Appendix A. 3 Superstructure-Deck section data



Appendix A.4 Vehicle Loading Data

Appendix A.4.1 Tandem load



Appendix A.4.2 HL-93M Tandem load

Vehicle Data - Vertical Loading

Uniform Load Scale Factor: 1      Axle Load Scale Factor: 1

Load Length Type	Minimum Distance	Maximum Distance	Uniform Load	Uniform Width Type	Uniform Width	Axle Load	Axle Width Type	Axle Width
Leading Load	Infinite		0.	Fixed Width	3.048	111.2056	Two Points	1.8288
Leading Load	Infinite		0.	Fixed Width	3.048	111.2056	Two Points	1.8288
Fixed Length	1.2192		0.	Fixed Width	3.048	111.2056	Two Points	1.8288
Trailing Load	Infinite		0.	Fixed Width	3.048			

Buttons: Add, Insert, Modify, Delete

**Floating Axle Loads**

Value      Width Type      Axle Width

For Lane Moments      0      One Point      1

For Other Responses      0      One Point      1

Floating Axle Load Scale Factor: 1

Double the Lane Moment Load when Calculating Negative Span Moments

Ignore Vertical Loads if Horizontal Centrifugal or Braking Loads are Defined

Buttons: OK, Cancel

**Superelevation Effects**

Adjust Vertical Loads for Superelevation

Axle Load Factor:

Uniform Load Factor:

Appendix A.4.3 Sino Truck Loading

Vehicle Data - Vertical Loading

Uniform Load Scale Factor: 1      Axle Load Scale Factor: 1

Load Length Type	Minimum Distance	Maximum Distance	Uniform Load	Uniform Width Type	Uniform Width	Axle Load	Axle Width Type	Axle Width
Leading Load	Infinite		0.	Fixed Width	3.	61.03	Two Points	1.8
Leading Load	Infinite		0.	Fixed Width	3.	61.03	Two Points	1.8
Fixed Length	1.37		0.	Fixed Width	3.	121.46	Two Points	1.8
Variable Length	3.4	3.7	0.	Fixed Width	3.	119.65	Two Points	1.8
Trailing Load	Infinite		0.	Fixed Width	3.			

Buttons: Add, Insert, Modify, Delete

**Floating Axle Loads**

Value      Width Type      Axle Width

For Lane Moments      0      One Point      1

For Other Responses      0      One Point      1

Floating Axle Load Scale Factor: 1

Double the Lane Moment Load when Calculating Negative Span Moments

Ignore Vertical Loads if Horizontal Centrifugal or Braking Loads are Defined

Buttons: OK, Cancel

**Superelevation Effects**

Adjust Vertical Loads for Superelevation

Axle Load Factor:

Uniform Load Factor:

Appendix A.5 Selection of Analysis Type

Appendix A.5.1 Moving load case for Static analysis

**Load Case Data - Moving Load**

Load Case Name: static [Set Def Name] Notes: [Modify/Show...]

Load Case Type: Moving Load [Design...]

Stiffness to Use:  Zero Initial Conditions - Unstressed State  
 Stiffness at End of Nonlinear Case  
 Important Note: Loads from the Nonlinear Case are NOT included in the current case

Directional Factors:  Vertical (1.0),  Braking/Acceleration,  Centrifugal

Assign Number	Vehicle Class	Scale Factor	Min Loaded Lanes	Max Loaded Lanes	Lanes Loaded
1	Tandem	1.	0	0	All

Multilane Scale Factors: [Table with 2 rows, 2 columns: Lanes Loaded, Reduction Scale Factor]

Mass Source: MSSSRC1

Lanes Loaded for Assignment 1: [List of Lane Definitions] Selected Lane Definitions: L lane, R lane

[OK] [Cancel]

Appendix A.5. 2 Time history case for dynamic analysis

**Load Case Data - Linear Direct Integration History**

Load Case Name: 40kmh [Set Def Name] Notes: [Modify/Show...]

Load Case Type: Time History [Design...]

Stiffness to Use:  Zero Initial Conditions - Unstressed State  
 Stiffness at End of Nonlinear Case  
 Important Note: Loads from the Nonlinear Case are NOT included in the current case

Modal Load Case: Use Modes from Case

Analysis Type:  Linear,  Nonlinear  
 Solution Type:  Modal,  Direct Integration,  Frequency Domain

History Type:  Transient,  Periodic

Load Type	Load Name	Function	Scale Factor
Load Pattern	Moving Load	half-cycle-si	1.
Load Pattern	Moving Load	half-cycle-sine	1.

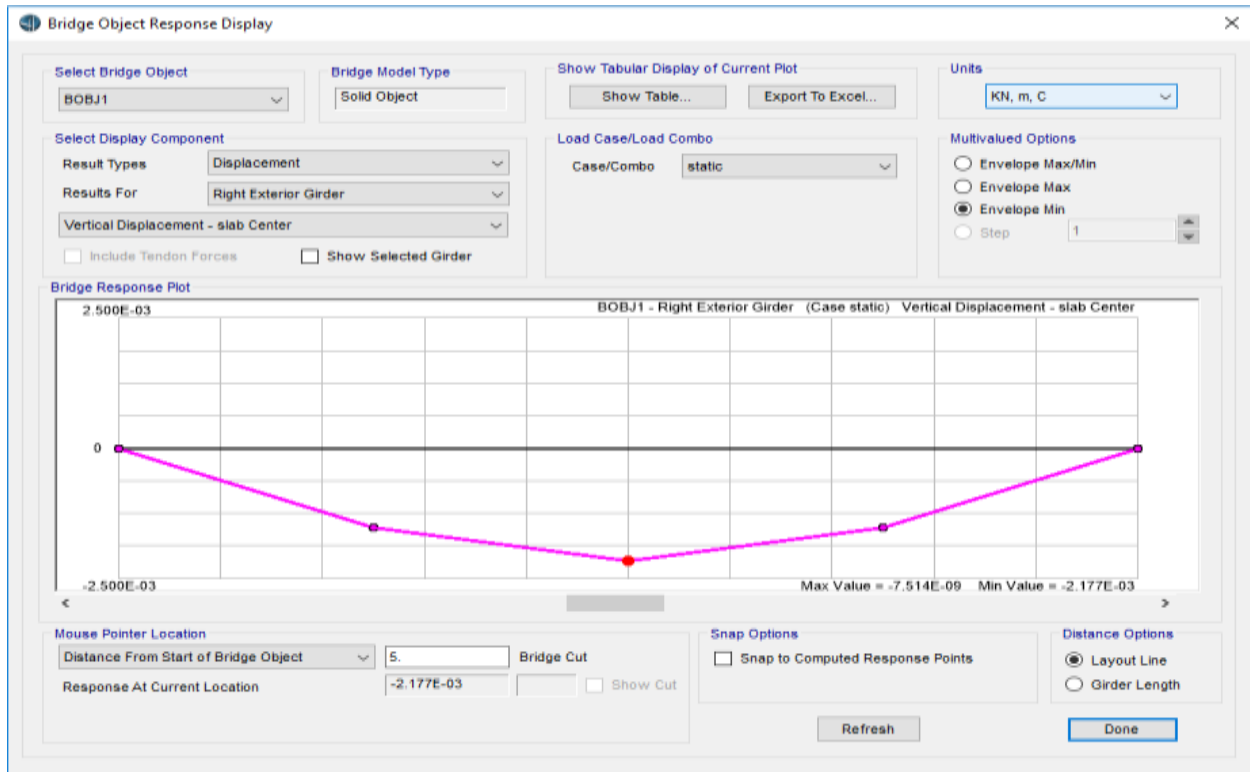
Mass Source: MSSSRC1

Time Step Data: Number of Output Time Steps: 240, Output Time Step Size: 5.000E-03

Other Parameters: Damping: None, Time Integration: Hilber-Hughes-Taylor

[OK] [Cancel]

Appendix A.6 Response Output- Mid span deflection



Appendix A.7 Vehicle load assignment

