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# WIM Based Calibration of AASHTO LRFD Live Load Model (HL-93) for Highway Bridges Design of Pakistan

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**Abstract –** *Among the impermanent loads on bridge structures, the most frequent one is a vehicular live load and plays a key role in design of the bridge components Most of the developed countries have a comprehensive highway bridge design specification while other countries adopt certain renowned design codes but with certain adjustments to meet their demands. Live Load Models are either modified or calibration factors are proposed for them. In Pakistan two different codes are being followed for highway bridge design i.e. West Pakistan Code of Practice for Highway Bridge (1967) and AASHTO LRFD. Both the codes live load models do not represent the actual load and traffic pattern in Pakistan. In this study a WIM data is analyzed, extrapolated to the design period and HL93 live load model is calibrated to represent the true traffic condition of Pakistan.*

***Keywords:*** *Live Load Model, AASHTO LRFD, WIM, Calibration, Acceleration, Probability, Traffic*

## I. INTRODUCTION

Bridges are the most essential part of transportation system and they need to be designed for all sorts of necessary loadings. The most essential load section among all is the live load in bridge design especially vehicular traffic loads. Traffic loads are the most multifarious variable loads that affect the design of bridges. Every country has different traffic pattern from one another and therefore it is necessary to develop a unique live load model for each of them. But in some countries two or more bridge design codes are used, for instance in Pakistan both West Pakistan Code of Practice for Highway Bridges (WPCPHB, 1967) & AASHTO LRFD or Standard specifications are used. A traffic live load models are developed to represent the actual traffic of the country or region and are meant to be conservative for new structures during their design life. The live load model should periodically be updated with the advancement of trucks industry & overloading for the safety of highway bridges. In Pakistan, current live load models in WPCPHB (1967) [1] were taken from British code (BS 153, 1937) introduced in India (in 1935) and is also based upon AASHTO standard of 1961 [2]. Since that time traffic pattern and truck loads have significantly changed especially vehicles GVW, axles weight and axles configuration while this code has not been updated since than to cater with the current load condition.

The ever-increasing global issue of overloading causes the deterioration of bridges whose carrying capacity are limited by their design. Infrastructure degradation due to higher axle loads are imposing huge maintenance cost. Due to fragmented trucking industry in Pakistan trucks are manufactured illegally with larger dimensions to carry more weights than normal trucks lead to overloading in Pakistan [3] In 2000, National Highway Authority has postulated the legal load limits on vehicular gross weight and axles weight [4] but unfortunately is not being followed. Similarly, Trucking Policy was formulated in 2007 to have checks on truck manufacturers, aiming on regulating and formalizing the trucking industry but unluckily has not been implemented.

## II. LITERATURE REVIEW

Nowak, (1993) carried out a comprehensive study in developing a live load model for bridges design. In this research, he used probability paper for extrapolation of extreme daily trucks load effects for getting the bridge design life moments and shears. Although this study was in continuity of previous study by Nowak and Lind for live load model of Ontario Highway Bridge Design Code (OHBDC) but latter on this study made a base Live Load (LL) model for the AASHTO LRFD. WIM data of Ontario (1977) was used in this study while the load model proposed is still in use in whole USA. Only extreme trucks were selected as a sample from the database and their load effects were calculated for various span lengths. The moments and shear were then extrapolated to 75 years return period using probability paper. These load effects were than divided by the load model of that time i.e. HS20 truck. The ratio clearly showed that the current traffic is no longer represented by HS20 truck or lane, so therefore, a new load model was required to cover the heavy loads. For this author combines the design truck with the lane load (except the knife edge load) for medium spans and tandem with the lane load for short spans. Nowak also studied the girder distribution factors using finite element method for various spans ranging from 30ft to 200ft and different girder spacing's. He found that the GDF's of AASHTO were on more safer side than the calculated ones [8]. The load model presented in this study is still the prevailing live load model since its development. Most of the states in USA calibrate this load model for their own truck traffic conditions.

Agarwal & Cheung, (1986) proposed a new live load prevailing loading condition in Canada of that time and compared the results with the previous load models. This was based on regular trucks under legal limits and author suggested that the overloading beyond the legal requirements will be covered in the live load factor. The new LL model developed was the CS-W, in which W was taken as 600 KNs as a base. A modified method was proposed and used for calculating the live load factors [9].

Miao, (2002) studied different statistical methods and proposed one for developing of live load model. In this study a statistical approach was proposed by Miao for developing of live load model as compared to the traditional probability paper method. Traffic flow data of five main routes in Hong Kong for 10 years were gathered from WIM stations installed on that routes. For statistical analysis, they split the traffic database in two categories i.e. loos traffic and dense traffic status. For extrapolation, they used statistical approach although they perfume it with the probability paper method as well for comparison but later on they used the first one for developing the live load model for Hong Kong. In conclusion of the two methods they found that the statistical approach is very complex and require extensive sample data. The obtained parameters from statistical approach of extrapolation were used as base for defining the live load model. A 5-axles truck was proposed as the design truck for the design of highway bridges in Hong Kong. [10]

Using extensive study of the WIM stations in Louisiana state, Sivakumar et al proposed calibration of AASHTO live load model using the simple extrapolation method and reliability technique. He observed that the normal truck traffic contains very heavy vehicles whose effects are much higher than HL-93 loading. He first filtered the WIM data for separating the truck types based on strength I and strength II limit state, then he found the ratio of the moments from these trucks to the design live load moments for span ranging 6m to 60m. The maximum moments for the span length below 37m was higher than the design live loading and he suggested multiplying design tandem by two for coping this issue. The modified HL-93 was then optimized by reliability analysis. [11]

A truck traffic study was conducted on the two years' database for calibration of the Turkish live load model for steel plate girders by Koc in 2013. The author compared the prevailing load model with HL93 load model and based on the survey data he proposed a new load model which was of same configuration of HL93 but with heavier weights and the design truck was called AYK45. Two probability papers were used i.e. Normal and Gumbel for linear fitting. Cumulative distribution function was extrapolated to 75 years' probability period by three ways, i.e. using overall data, using the upper ten percent(extreme) data, using only upper tail. For reliability analysis, extreme data & overall data extrapolation was taken based on research reviews. Reliability index of 4 was taken as target for extreme data with the resistance factor of 1.0 and the live load factor of 1.75 but the fact is the AYK45 is heavier than HL93. [12]

HL-93 Live load model was reviewed by well-known researchers of Europe i.e. Leahy, OBrien, Enright and Hajializadeh using huge data of 17 WIM stations containing seventy-four million vehilces. The aim of this study was to achieve consistent level of conservation and to eliminate over design or under design of bridges in certain area's. In this study proposed a new simple UDL type load model to truly represent the traffic conditions which was then compared with the different WIM stations data [14].

## III. WEIGH IN MOTION DATA

For case study truck traffic data was taken from Mulan Mansoor Weighing station on National Highway (N-5) and was statistically analyzed. By volume, trucks are classified based on axle number as shown in **Error! Reference source not found.**. which clearly shows that two axle trucks are dominating in number and are sixty-one (61%) of total truck traffic. Second most is the 3-axles (type 2) truck with 28%. Five axle trucks are the least among the composition. It can also be observed that over half of the vehicles are overloaded and among the vehicles type 3 is more overloaded as compared to others. Table.1 shows the maximum, mean values as comparison with National Highway Authority (NHA) legal limits, which clearly shows that 2 & 3 axles trucks maximum are double then the legal limits and also the mean of these two truck types are over than legal limits. It means that the most killing vehicle types are 2 &3 axles.

**Table.1:** Descriptive statistics of GVW (Tons) of trucks

| Truck Type | 2 Axles | 3 Axles | 4 Axles | 5 Axles | 6 Axles |
|---|---|---|---|---|---|
| NHA Legal | 17.5 | 29.5 | 41.5 | 51.5 | 61.5 |
| Mean | 17.4 | 33.3 | 34.8 | 48.6 | 55.3 |
| Max | 40.2 | 61.4 | 71.9 | 85.3 | 91.5 |

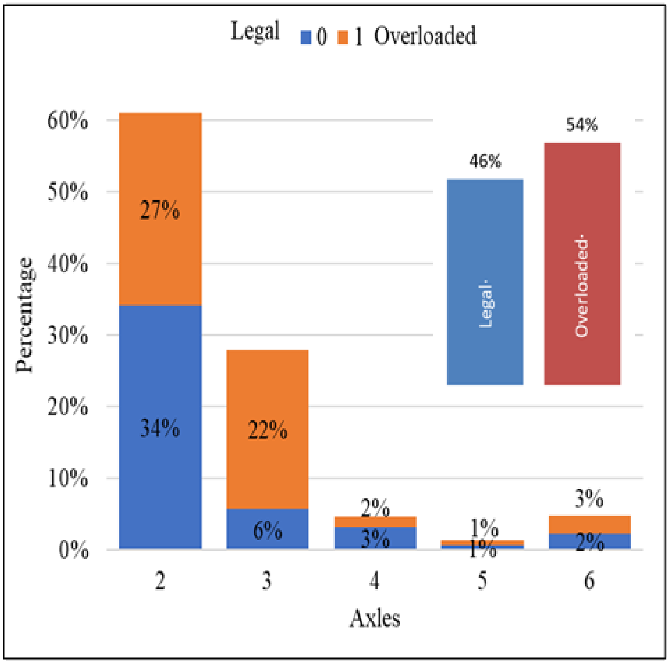


Figure.1 Truck Traffic Composition & Overload Percentage

## IV. STATISTICAL EXTRAPOLATION OF LOAD EFFECTS

The truck survey data is available for about one month which contains about 50,000 trucks but for a long period like the design life of bridge usually 75 years we need statistical extrapolation. Different types of probability distribution can be fitted on the histogram of load effects i.e. moments and shears but certain goodness to fit methods are available for finding the distribution function which best fit or suits the actual distribution of moment/shear. In proposing HL93 live load model normal probability distribution function was used although it doesn't fit well but the tail portion did [13]. Similarly, in this study the normal probability paper is used for linearly extrapolating the tail whose probability distribution function is given in equation Eq.1.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \qquad \text{Eq.1}$$

The cumulative distribution function can be expressed in terms of standard score i.e. Z-score as given in equation Eq.2

$$\Phi(z) = \int_{\infty}^{z} \frac{1}{\sqrt{2\pi}} exp\left[-\frac{z^2}{2}\right] dz \qquad \text{Eq.2}$$

The inverse of the standard normal cumulative probability distribution function as given in equation Eq.3 is used as vertical axis of the normal probability paper.

$$z = \Phi^{-1}(p) \qquad \text{Eq.3}$$

The procedure for plotting the load effects on probability paper is that the load effects are sorted in ascending order, number of trucks (n) is found, the cumulative probability of first load effect will be P1=1/n while for 2nd will be

P2=1/n+P1 and for other Pn=(1/n)+P(n-1). Then from probability of each load effect the vertical axis of probability paper is found by equation Eq.3 and can easily be calculated in Microsoft Excel by a formula NORM.S.INV(probability). The horizontal axis of the probability paper represents the load effects or normalized load effects. Better to normalize the load effect of each truck in a survey data by HL93 for calibrating and for finding the extrapolated 75-year loading.

Although the average daily truck traffic of the survey data is 1,643 and the data gathered is for the Grand Trunk (GT) Road which has heavy truck traffic as compared to other routes but for this study the average daily truck traffic, ADTT=1,000 was taken as a base for extrapolation and certain corrections factors for other ADTT are also calculated as well. If ADTT =1000 then the probability of exceedance is 0.001 and Y-ordinate or Z value for this can be found as Z= $\Phi^{-1}(0.001)$ = 3.09. Similarly, in 75 years the average number of trucks will be 27 million as there will be 27 thousand days in 75 years, so the probability = 3.07E-08 and Z-ordinate value for probability paper comes out to be and 5.38 and each load effect tail will be extrapolated to this value. Different researchers have used different techniques for tail fitting like (Castillo, 1988) used Weibull distribution for fitting top 2*square root of N, where N is number of events, Sivakumar & Ghosen, used top 5% data for linearly extrapolation [6] and (Nowak, 1999) used normal probability paper and the only the tail portion were arbitrarily projected. For this study, Prof. Nowak method is used which is the simplest but taking the whole data rather than block maxima and only linear tail fitting was adopted. For different time period projection, the ratio of the load effect by each truck to load effect by HL93 is plotted over CDF and the linear potion of the tails were linearly extrapolated to the ordinate of 5.38 as shown in Figure 2 and Figure 3.

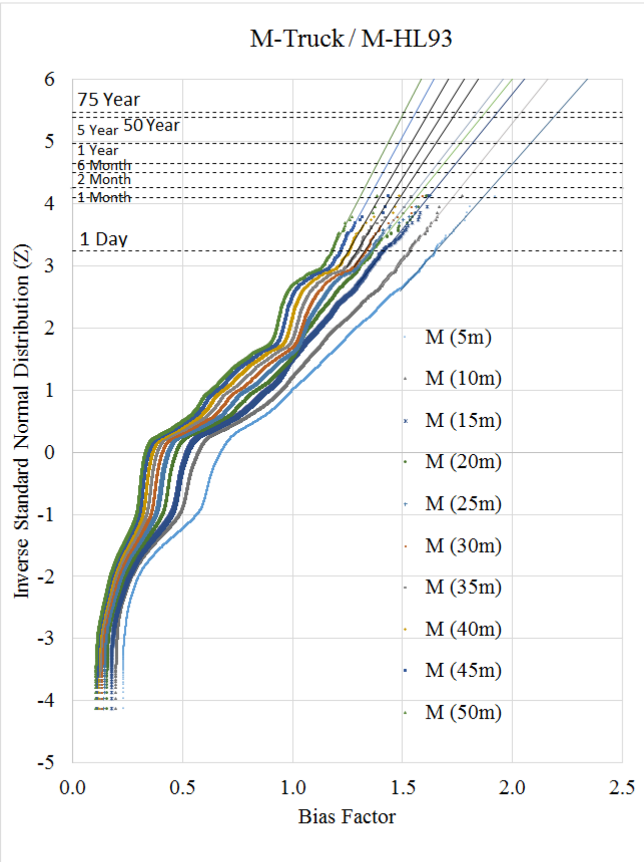


Figure. 2: CDF of M-Truck / M-HL93

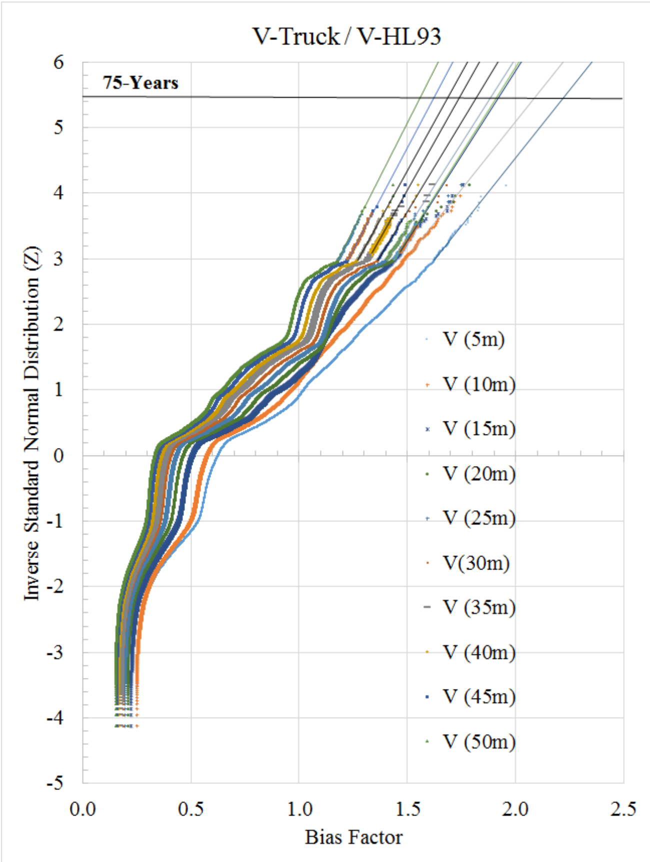


Figure.3: CDF of V-Trucks / V-HL93

It can be observed from graphs of CDF that the load effects are not normally distributed and for both moments and shears above 25m span the CDF have undulation in the tail but certain portion of the tail is linear mean normally distributed which is linearly extrapolated. The extrapolated shear (VTruck) and moments (MTruck) ratio of the trucks to HL93 is reported in Figrue.4 and Figure 5.

 

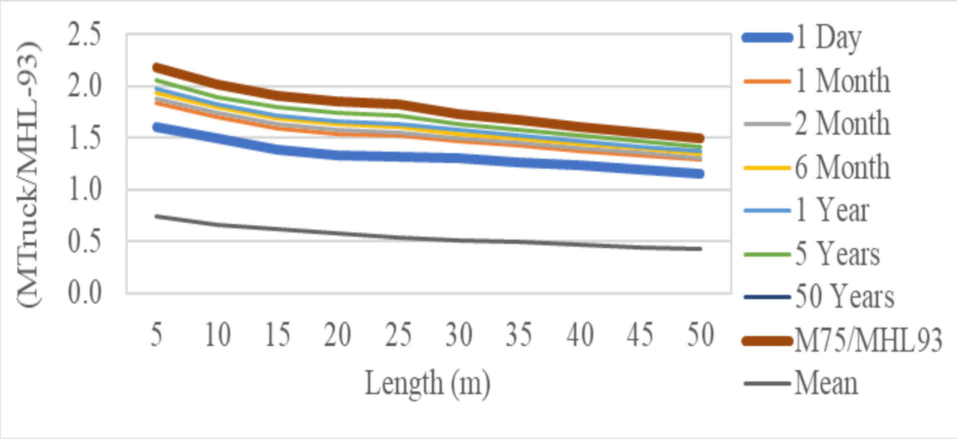


Figure.4: Simple Span Moments Ratio of Trucks and HL93

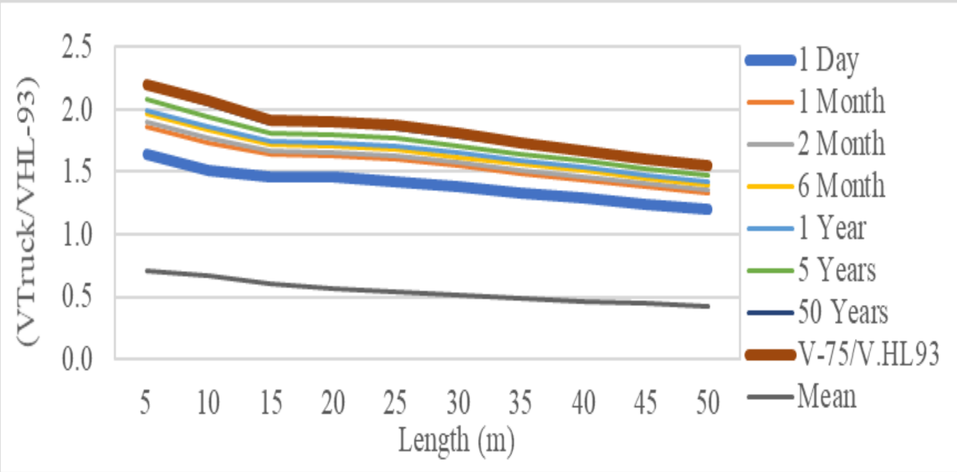


Figure.5: Simple Span Shear Ratio of Trucks and HL93

It clear from Figrue.4 and Figure 5 that the ratio for 75-year probability moments (MTruck) are 2 to 1.5 for span 5m to 50m respectively, which shows that the HL93 load is not representing truck loading in Pakistan and need to be calibrated. Other lower time period load effects ratio was also calculated like 5-years extrapolated effects which can be used for the assessment of the existing bridges. The mean value of the load effects ratio is also plotted in graph which is much lower than the 75-years load effects. All the load effects calculated based on single truck in one lane, multi truck in single lane effects are not considered as no multi truck events was found in the survey data.

### 4.1 Extrapolated Load Effects

By multiplying the ratio given in above table with HL93, the 75-year moments and shears are calculated as reported in Table.2 also graphically in Figure.6 and Figure.7.

**Table.2:** "75-Years" Extrapolated Live Load Effects

| Span (m) | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
|---|---|---|---|---|---|---|---|---|---|
| M 75 (KN-m) | 1210 | 2080 | 3130 | 4273 | 5294 | 6407 | 7501 | 8599 | 9719 |
| V 75 (KN) | 568 | 626 | 695 | 745 | 772 | 787 | 807 | 817 | 826 |

 

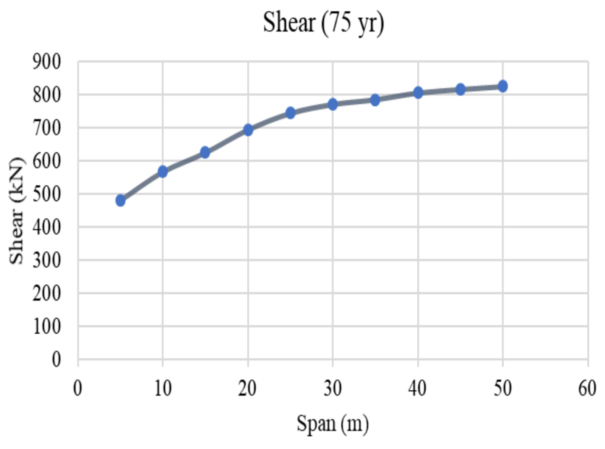


**Figure.6:** Extrapolated Shear (75 Yr. Probability)

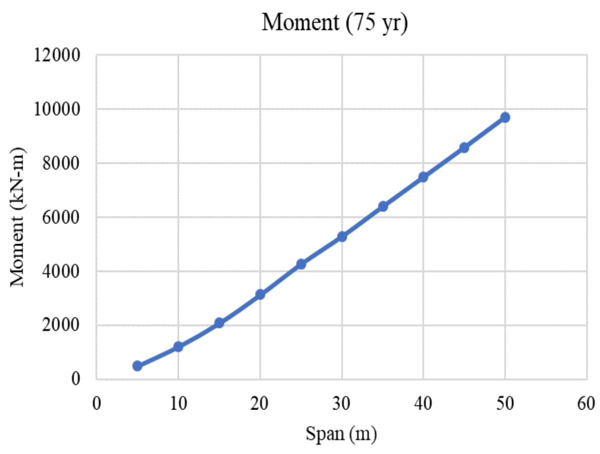


**Figure.7:** Extrapolated Moments (75 Yr. Probability)

### 4.2 Traffic Growth Factors

It is obvious that traffic varies with time and also different territory have different average daily truck traffic. If the average daily truck traffic is 1,000 then the number of trucks for the design life (75 year) can be 27 million but will goes to 135 million trucks for ADTT of 5000. For different span lengths (5m – 50m), various time period (1 day to 75 years) values can be obtained with increasing growth (ADTT of 100 to 5,000. The weighing station surveyed has average daily truck traffic of 1,653 and this is the grant truck road but most of the areas have ADTT less than 1,000 except few industrial areas or ports. Taking ADTT of 1,000 as a base mean the growth factor is one, so the growth factor with increase in truck traffic the design moment will increase vice versa. For ADTT of 5,000 the increase is about 3% while for lower values like 100 the decrease is approximately 4% as shown in Figure.8 and Figure.9.

The variation with growth is nonlinear and decreases much as compared to the increase with the increase in traffic as clear from the Figure 8&9, this may depend on the distribution function used for tail fitting.

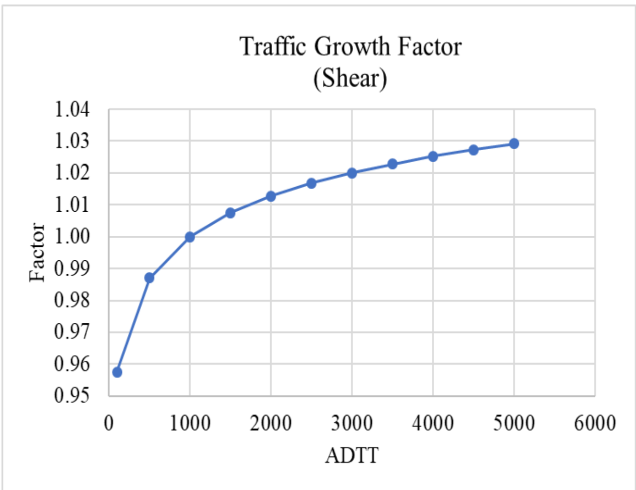


**Figure.8:** Traffic Growth factor for shear

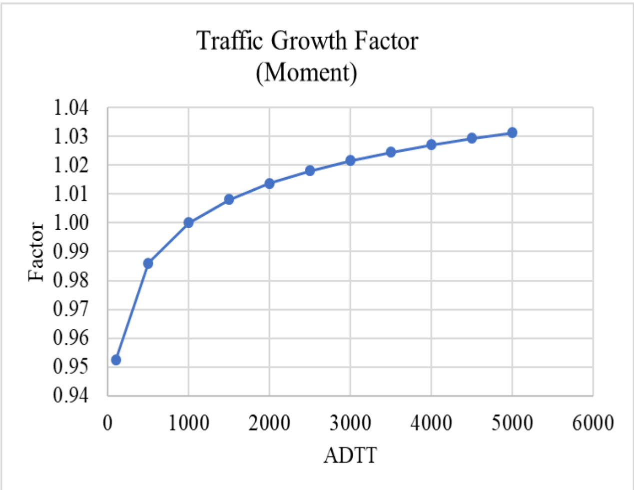


**Figure.9:** Traffic growth factor for moment

## V. Calibration of HL93 live load model

AASHTO LRFD specifications are adopted by many countries because it is comprehensive and is periodically updated. Certain adjustments are made before adopting any specification and mostly the live load models and LL factors are calibrated to cater with the loading conditions. Similarly, the author calibrated the HL93 load model according the current truck traffic conditions and also based on extrapolated load effects. The calibrated HL93 is composed of the same live loads but certain factors are multiplied to achieve the target live load moments and shears as shown in Figure.10**:** .

 

The factors are 2.5 for design truck, design tandem, and 0.3 for design lane. The maximum of the two combination is taken as the design loads i.e.

$$\text{Maximum of} \begin{cases} \mathbf{2.5} \text{ x HS20 Truck} + \mathbf{0.3} \text{ x Design Lane} \\ \textbf{or} \\ \mathbf{2.5} \text{ x Design Tandem} + \mathbf{0.3} \text{ x Design Lane} \end{cases}$$

Dividing the load effects of 75-years by calibrated HL93 gives approximately uniform ratio of 1.0 as shown in Figure.10, which means that the model is calibrated to the design period load effects.

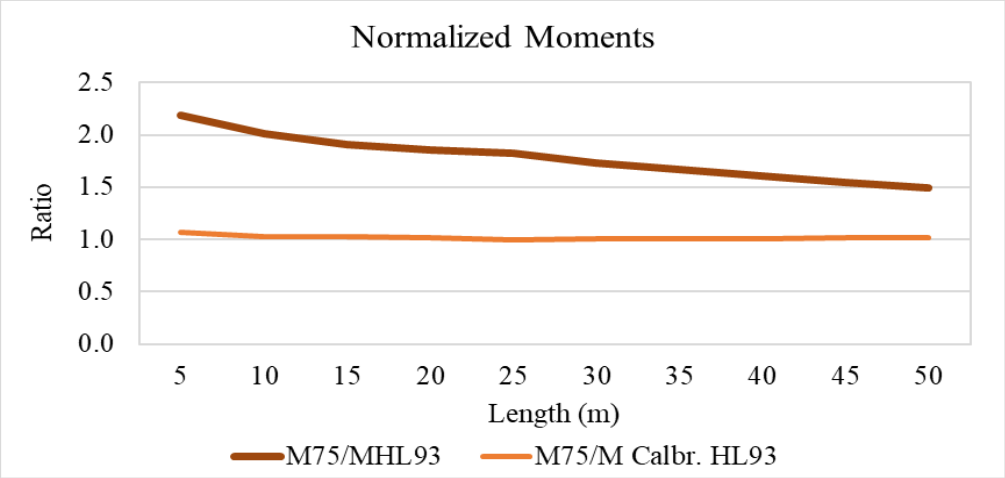


**Figure.10:** Normalized moments Comparison of Calibrated LL model with

## VI. CONCLUSION & RECOMMENDATION

### 6.1. Conclusions

On the basis of this research work, the following conclusions were drawn

1. From the results of the study it is concluded that HL-93 live load model doesn't represent the prevailing traffic in Pakistan and new live load model shall be proposed.
2. The extrapolated load effects from traffic data is 2.0 to 1.5 times of HL-93 for 5m to 50m span respectively.
3. As the average daily truck traffic varies, therefore a growth factor shall be multiplied with the design load effects.
4. HL93 live load model is calibrated to reflect the surveyed truck traffic i.e. by multiplying the design truck and design tandem with 2.5 and a design lane with 0.3.

### 6.2. Recommendation

1. It is suggested that a live load factors should be proposed for prevailing live load models in Pakistan using current practice of reliability analysis to have uniform level of safety.
2. It is recommended to use the calibrated HL93 Live Load Model in future design of bridges.
3. It is recommended to use large data of various WIM stations of the main routes of Pakistan for proposing a bridge design loads.

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