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A monte-carlo simulation for the estimation of side-by-side loading events on oregon bridges

Oregon köprülerinde yan yana araç yüklemelerinin tahmini için bir monte carlo simülasyonu

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A Monte-Carlo Simulation for the Estimation of Side-by-Side Loading Events on Oregon Bridges

Araştırma Makalesi / Research Article

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ABSTRACT

Obtaining the side-by-side probabilities accurately is a very important procedure during two lane loaded live load factor analysis. To calculate the load factors properly, side-by-side loading events should be investigated very carefully. This study presents a statistical method to investigate the side-by-side events on the Oregon bridges. Numerical simulations were performed for this investigation. These simulations were developed in MATLAB. Gross vehicle weights (GVW) of the trucks were used during the analysis. Monte Carlo simulations were performed to analyze side-by-side loading events. Degree of correlation coefficient of GVW for side-by-side trucks were also obtained from Monte Carlo simulations. 290 bridges located at the prescribed mile markers on Interstate-5 (I-5) southbound on Oregon highways and 1-year of Oregon state-specific weigh-in-motion (WIM) data were used. 75,000 trucks were randomly selected from 1,787,612 trucks that correspond to 1-year WIM data from Woodburn NB traffic site that is located in Oregon. Inverse standard normal distribution functions and cumulative distribution functions of the truck data were generated. With respect to the statistical analysis, side-by-side loading probabilities were found to be smaller than the ones presented in American Association of State Highway and Transportation Officials LRFD calibration.

Keywords: Bridge, civil engineering, highway, monte carlo simulation, side-by-side loading.

Oregon Köprülerinde Yan Yana Araç Yüklemelerinin Tahmini için Bir Monte Carlo Simülasyonu

ÖZ

İki şeritli yollardaki hareketli yük katsayılarının tayininde, yan yana araç yüklemelerinin belirlenmesi çok önemli bir aşamadır. Yük katsayıları belirlenirken yan yana araç yüklemeleri çok dikkatli bir şekilde hesaplanmalıdır. Bu çalışmada, Amerika'da bulunan Oregon eyaleti köprülerindeki yan yana araç yüklemelerinin ve brüt araç ağırlıkları korelasyon katsayılarının tayini için istatistiksel bir yöntem sunulmuştur. Bu yöntemde bir Monte Carlo simülasyonu geliştirilmiş ve uygulanmıştır. Hesaplamalar esnasında kamyonların brüt araç ağırlıkları göz önüne alınmıştır. Analizlerde MATLAB programında hazırlanan sayısal simülasyonlar kullanılmıştır. Sayısal simülasyonlarda, Oregon eyaletindeki eyaletler arası I-5 otoyolunda, güneye giden doğrultuda bulunan 290 köprünün bilgileri ve 1,787,612 adet kamyonun, hareket halinde tartma (WIM) verileri kullanılmıştır. Köprü verileri köprülerin I-5 otoyolu üzerindeki geçiş km değerleri, bir diğer deyişle gerçek mil işaretlemeleri ve gerçek köprü uzunluklarıdır. Monte Carlo simülasyonlarında ayrıca 75,000 adet rassal (rastgele seçilmiş) kamyon kullanılmıştır. Bu kamyon verileri kullanılarak standart normal dağılım fonksiyonları ve kümülatif dağılım fonksiyonları hesaplanmıştır. İstatistiksel analizler sonucunda yan yana yükleme olasılıkları, Amerikan otoyol ve taşıma standartlarını belirleyen kurum olan AASHTO'nun hazırladığı köprü tasarım şartnamelerindeki (LRFD) değerlerinden daha düşük olarak bulunmuştur.

Anahtar Kelimeler: Köprüler, inşaat mühendisliği, karayolu, monte carlo simülasyonu, yan yana yükleme.

1. INTRODUCTION

Weigh-in-motion (WIM) devices are designed to capture and record the axle weights, and gross vehicle weights as vehicles drive over a measurement site. WIM data are obtained from the measurement of these devices, during the traffic. In load factor calculations [1-2] WIM data is being used widely. A method was proposed in [4] for calculating site-specific load factors, using truck weight data from WIM sites that follows the format used in the derivation of live load factors contained in the specifications [3]. This approach is to determine the statistics associated with the Oregon type truck (3S2 truck) population to characterize the uncertainty associated with the alongside truck. Accurate calculation of multi-lane load factors is crucial during the estimation of side-by-side loading events. The investigation on multi-lane load factors and side-by-side loading events have being studied by researchers during the last decade [5-7]. The jurisdictional and enforcement characteristics of Oregon, the modifications used to describe the alongside truck population based on the unique truck permitting conditions in the state, the WIM data filtering, sorting, and quality control, as well as the calibration process, and the computed live load factors, were presented in [5]. A framework for multi-lane factors (MLFs) for bridge traffic loading was proposed in [6]. Example application of the framework of a site using WIM data was demonstrated in their study. Two, three, and four-lane transverse reduction factor based on

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probability theory and the recently actual traffic flow data were presented in [7]. Live load factors of Oregon bridges were calculated by using WIM data and statistical approaches in [8]. Distribution factor equations that accurately predict the distribution factor of the decked precast and prestressed concrete girder bridge systems when it is subjected only to single-lane loading were given in [9]. Lately Monte Carlo simulation is being studied increasingly in bridge engineering research [10-15]. However, side-by-side loading event estimation studies through Monte Carlo simulation are rare. A comprehensive model for Monte Carlo simulation of bridge loading for free-flowing traffic and presentation of how the model matches results from measurements on five European highways was given in [10]. Through Monte Carlo simulation, seismic analysis was carried out to take into account the variability of certain factors relating to the seismic input of a bridge in [11]. Monte Carlo Simulation technique was integrated to quantitatively estimate the basic probabilities and to produce robust overall bridge condition ratings in [12]. In order to estimate the probabilistic response of a bridge, obtaining the simulation number with the exact solution through Monte Carlo Simulation and determining the type of statistical distribution were carried out in [13]. The dynamic response of floating bridges subjected to harsh weather condition was predicted in the time domain using Monte Carlo simulations in [14]. A framework for probabilistic analysis of bridge networks based on system reliability and Monte Carlo simulation was carried out in [15]. An interesting Monte Carlo simulation application was studied to provide the probable effect of bismuth shielding on dose reduction to organs and investigation of applicability of Monte Carlo (MC) method in [16]. A statistical regression analysis on the estimation of the amount of earthquake induced permanent Ground displacements using strong ground motion records in Turkey was carried out in [17].

As it can be indicated from the previous paragraph, Monte Carlo simulation integration on bridge studies are mostly on seismic analysis of the bridges, bridge rating, probabilistic response of the bridges, time domain analysis and reliability analysis. However, a Monte Carlo simulation process on side-by-side loading analysis, for the Ohio WIM data was performed in [18]. This is one of the few studies on Monte Carlo implementation on side-by-side loading event calculation. In their example the number of trucks in the sample was 1,530. It was suggested in [18] that, the higher number of data sample available to the number of data points extracted, the better the results. Therefore, in this study 75,000 trucks were used in the analysis.

In this paper Monte Carlo simulation was implemented for the estimation of side-by-side loading events on Oregon bridges. A MATLAB code was written for performing the simulations. For calculating side-by-side loading events 290 bridges on I-5 highway were considered during the simulation procedure. I-5 is the main interstate highway on the West Coast of the United States, running largely parallel to the Pacific coast of the continental U.S. from Mexico to Canada. Average daily traffic data (ADTT) effect was considered in the simulations. Therefore 1-year data from WIM site of Woodburn Northbound (NB), which has the highest traffic density among the Oregon highways were used in the analysis. After performing Monte Carlo simulations through the 290 bridges on I-5 southbound, the side-by-side loading probabilities were obtained. The results were compared with the ones given in the calibration of [3].

2. MONTE CARLO SIMULATION FOR SIDE-BY-SIDE LOADING EVENTS

In this section before presenting the specific Monte Carlo Simulation approach for side-by-side loading events in Oregon bridges, information on Monte Carlo Simulation method is given.

2.1 Monte Carlo Simulation Method

Monte Carlo simulation is an efficient approach for the reliability analysis of engineering systems. In Monte Carlo simulation method, the uncertainties are defined with random variables. Although the values of random variables in a certain case are unknowns, the numerical range of the values of these random variables can be obtained. To obtain these values, firstly random numbers that vary between 0 and 1 are generated. After that, by using inverse cumulative distribution method (CDF), the numbers are transformed into random numbers that are generated for uniformly distributed variables [19-20]. Then the problem is evaluated deterministically for each set of realizations of all the random variables. The other step is the extraction of probabilistic information from N number of realizations. And lastly the accuracy of the method is determined. In this study, normal distribution was used as a distribution function, as it is suitable for the random parameters generated in this paper. However, there are several distribution functions like log-normal, uniform, Weibull, exponential etc. The Monte Carlo method is defined briefly with the basic equations below. In generating random numbers, CDF of the random variable is equated to the generated random variable with the following formula [20].

$$x_i = F_X^{-1}(x_i) = u_i \tag{1}$$

where CDF of a random variable is a method to describe the distribution of random variables. In Eq. 1, x_i is the certain value and $F(x)$ is the CDF which can be presented as

$$F_X(x) = \int_{-\infty}^{x} \frac{1}{\sigma_x\sqrt{2\pi}} e^{-\frac{(x-\mu_x)^2}{2\sigma_x^2}} dx \tag{2}$$

where μ_x is the mean of the random variables and σ_x is the standard deviation of them and the normal distribution formula is written below

$$F(x,\sigma,\mu) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (3)$$

For the solution of CDF which has normal distribution that is given in Eq. 1, the random numbers (u_i) between 0 and 1 are converted to standard normal random numbers (s_i) as given below

$$s_i = \frac{x_i - \mu_x}{\sigma_x} \quad (4)$$

The CDF of standard normal random parameter can be defined as

$$\Phi(s_i) = \int_{-\infty}^{s} \frac{1}{\sqrt{2\pi}} e^{-\frac{s^2}{2}} ds \quad (5)$$

and then this expression is equated with u_i as shown below

$$u_i = F_x(x_i) = \Phi(s_i) = \Phi\left(\frac{x_i - \mu_x}{\sigma_x}\right) \quad (6)$$

lastly the x_i of the random variable X with normal distribution can be obtained as

$$x_i = \mu_x + \sigma_x s_i \quad (7)$$

More information on Monte Carlo simulation can be obtained in [20-21]. The statistical approach and Monte Carlo simulation for the specific problem studied in this paper is defined below.

2.2 Calculation of Side-by-Side Loading Events for Oregon Bridges

WIM data time stamps and Monte Carlo simulation of statistical load effects were used to establish side-by-side loading events. Details of Woodburn NB records are shown in Table 1. The multiple presence factors of the trucks and degrees of correlation coefficients were obtained using Monte Carlo simulations.

Table 1. Details of Woodburn NB WIM records

Corridor	Site Location	Site Designation	ADTT	All Year Data
I-5	Woodburn NB	WBNB	5550	1,787,612

The real bridge span lengths and starting milepost locations along I-5 southbound were used in the Monte Carlo simulation procedure. While the WIM data from Woodburn NB was used for selecting 75,000 random trucks. The bridges included in the simulations are reported in [8]. The first page of the bridge log (mile markers, bridge names, and total bridge length) is given in the Appendix of this paper. However, the information of the remaining bridges can be found in [8]. The bridge log was obtained from Oregon Department of Transportation (ODOT). There were a total of 290 bridges included in the simulations. The Monte Carlo simulation process was executed by as follows:

- Assemble the GVW data representing the trucks from the Woodburn NB WIM site in the truck travel lane into a population consisting of 75,000 trucks (correspond to two weeks of WIM data ADTT = 5,000). Randomly select 75,000 trucks out of the 1-year population of WIM data consisting of 1,787,612 trucks.
- Assemble the GVW data representing the trucks from the Woodburn NB WIM site in the passing lane into a population consisting of 75,000 trucks (correspond to two weeks of WIM data with ADTT = 5,000). Randomly select 75,000 trucks out of 1-year of WIM data consisting of 1,787,612 trucks.
- Randomly select the truck identification number (truck id), truck GVW, truck velocity from the main lane population by implementing Monte Carlo method.
- Randomly select the truck identification number (truck id), truck GVW, truck velocity and the real time stamp that was calculated from the real WIM data from the passing lane population by implementing Monte Carlo method.
- Calculate the arrival and leaving time of the truck from the main lane population to the real bridge on I-5 considering the distance and length of the bridge.
- Calculate the arrival and leaving time of the truck from the passing lane population to the real bridge on I-5 by taking into account of the real time stamp of the passing lane truck.
- Compare all the arrival and leaving times of the trucks from the main lane and passing lane. If the arrival or leaving times are equal for the main lane and passing lane trucks, then it is a single side-by-side event. And the corresponding side-by-side trucks should be taken out of the populations.
- Repeat the whole Monte Carlo simulation process for each of the 290 bridges on I-5 southbound.
- Take the sum of all the single events for each bridge to obtain the total of side-by-side events on the corresponding bridges.
- Divide the number of side-by-side events by total number of trucks (75,000) to obtain the side-by-side probability.
- Store the GVW and truck id information of the side-by-side trucks for each bridge.

Calculation of the arrival and departure times of the trucks from the main lane and passing lane over a single bridge is illustrated in Figure 1.

The arrival time of the truck in the main lane to the bridge can be written as:

$$T_{1A} = D_i / V_{1j} \quad (8)$$

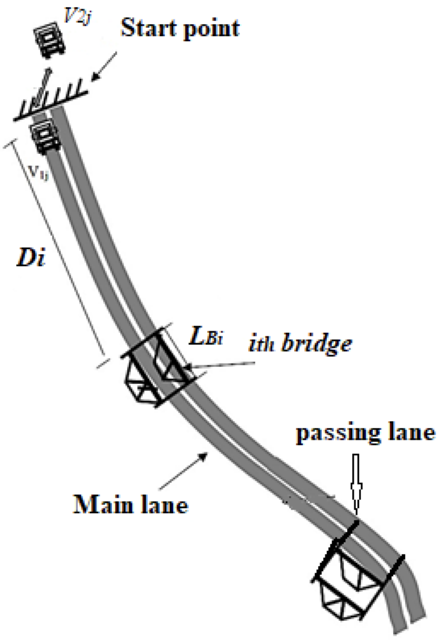

Figure 1. Illustration of simulation of truck coincidence on bridges along I-5.

where D_i is the distance of the *i*th bridge (i=1….290) to the starting point on I-5 southbound. And V_{1j} is the velocity of the *j*th truck (j=1….75,000) on the main lane as depicted in Figure 2. The leaving time from the bridge can be expressed as:

$$T_{1L} = D_i + L_{Bi} / V_{1j} \tag{9}$$

where L_{Bi} is the length of the *i*th bridge on I-5 southbound. The arrival time of the truck on passing lane to the *i*th bridge is

$$T_{2A} = D_i / V_{2j} + \Delta t_j \tag{10}$$

in this equation V_{2j} is the velocity of the *j*th truck on passing lane, Δt_j is the time separation between the truck on the main lane and *j*th truck on the passing lane. Time separation values were obtained from the real WIM data time stamps. The actual time stamps throughout the full year of Woodburn NB WIM site data were used to generate time separation Δt_j for each truck. The leaving time of the truck on passing lane to the *i*th bridge were calculated as:

$$T_{2L} = (D_i + L_{Bi}) / V_{2j} + \Delta t_j \tag{11}$$

The arrival and departure times on the bridge for each truck in the main lane and passing lane were compared with each other and the total number of side-by-side events were calculated as explained above. Schematic representation of the Monte Carlo simulation for side-by-side trucks is presented in Figure 2.

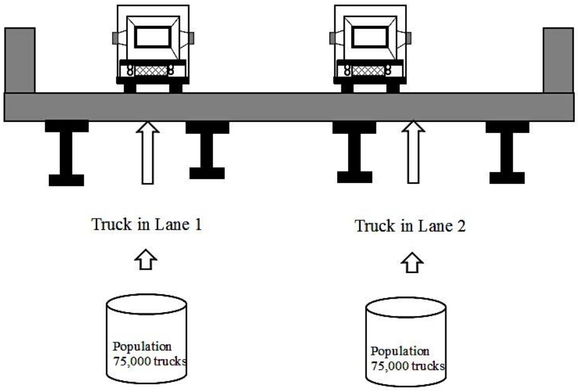

Figure 2. Schematic representation of side-by-side MonteCarlo simulations.

For Woodburn NB all year WIM data, the statistical information (the GVW and the velocity of the trucks) is shown in Figure 3. As it can be indicated from Figure 3 that, the GVW's of these trucks range from almost 1 ton to 100 tons (2 kips to 220 kips). In addition, the velocities of the corresponding trucks range from, 16 km/h to 150 km/h (10 mph to 95 mph). Moreover, the inverse standard normal distribution of all year truck data with respect to GVW is shown in Figure 4. As it can be indicated from Figure 4 that, for the trucks with GVW ranging from 1 ton to 100 tons the inverse standard normal distribution function values range from -4.87 to 4.87. Cumulative distribution function (CDF) of the truck data with respect to the time separation values of the side-by-side trucks is presented in Figure 5. CDF values start from 0.48. Time separation between the side-by-side trucks ranges from 1 to 100,000 seconds. CDF is normally distributed.

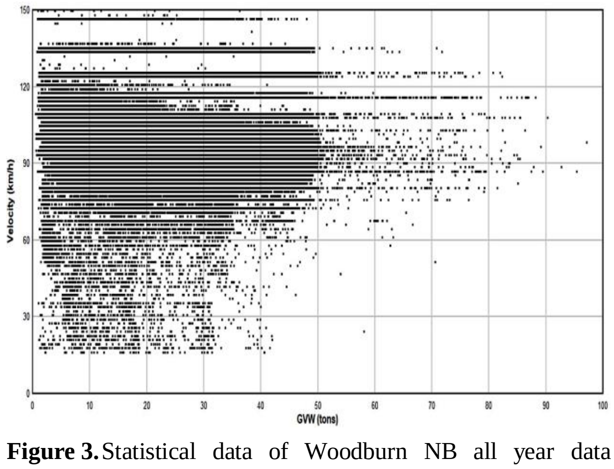

Figure 3. Statistical data of Woodburn NB all year data 1,787,612 trucks.

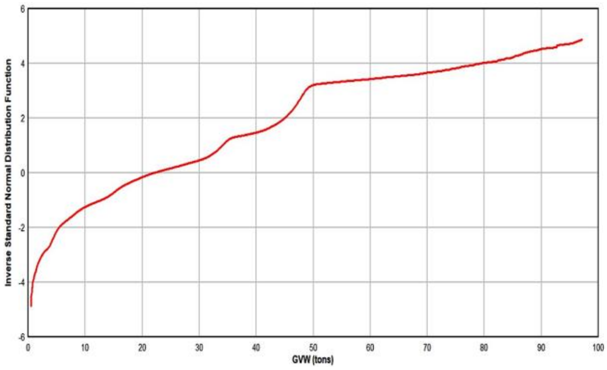

Figure 4. Inverse Standard Normal Distribution of GVW on all year data.

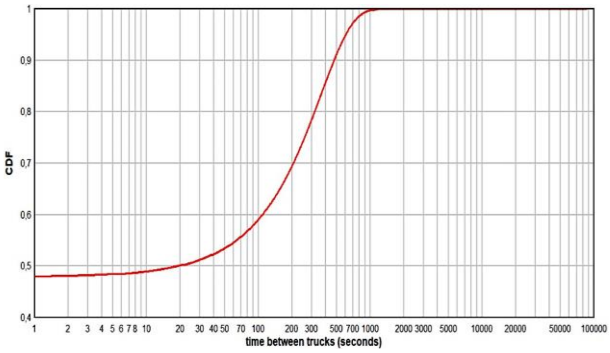

Figure 5. Cumulative Distribution function of the Truck Data.

After performing the simulations and obtaining the side-by-side events, the degrees of correlation between the side-by-side trucks for each bridge were calculated. The GVW of the main lane and passing lane trucks for each side-by-side event identified on a bridge during the Monte Carlo simulations were used to obtain the degree of correlation between the trucks. The correlation coefficient (ρ) equation between two random variables *X* and *Y* with expected values μ_x and μ_y and standard deviations σ_x and σ_y are given as:

$$r = E\left[(X - m_X)(Y - m_Y)\right]/s_X s_Y \qquad (12)$$

where E is the expected value operator.

Matlab and Microsoft Excel spreadsheets were used to obtain correlation coefficients for each bridge and side-by-side loading event. The side-by-side event numbers vs. the bridge lengths are given in Figure 6 for the half of the bridges. Total number of the bridges in Figure 6 is 145. The same results for the other half are shown in Figure 7. Each marker in Figures 6 to 9 represents a single bridge on I-5 southbound. Bridge span lengths range from 1.22 m (4 ft) to 567 m (173 ft). As seen in Figure 6, the bridge span lengths did not strongly influence on number of side-by-side events. It can be indicated from Figure 6 and 7 that side-by-side event numbers range from 30 to 67. The majority of the bridges have a span length ranging between 50 to 100 m. The side-by-side probabilities vs. the degree of correlation for the corresponding half of the bridges are given in Figure 8. The side-by-side probabilities of the other half of the bridges are shown in Fig. 9. As given in Figures 8 and 9, the degree of correlation ranged from 0.40 to -0.54 for the different bridges and the side-by-side probability (P*s/s*) range from 0.005 to 0.0075.

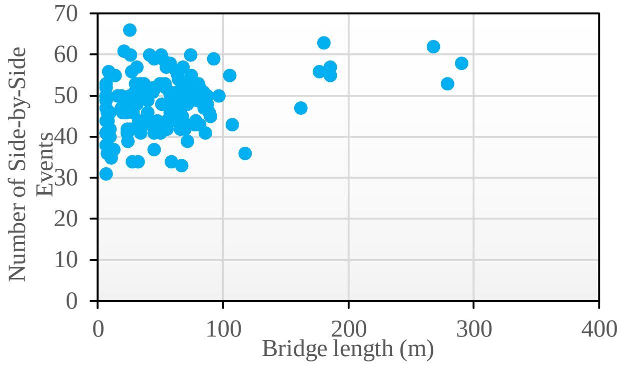

Figure 6. Side-by-side event numbers for bridges on I-5 - half of the 290 bridges.

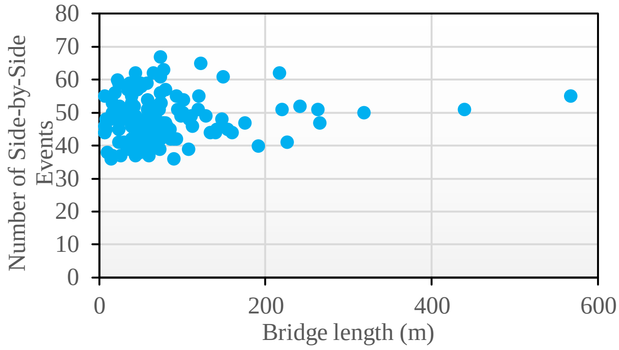

Figure 7. Side-by-side event numbers for bridges on I-5 - half of the 290 bridges.

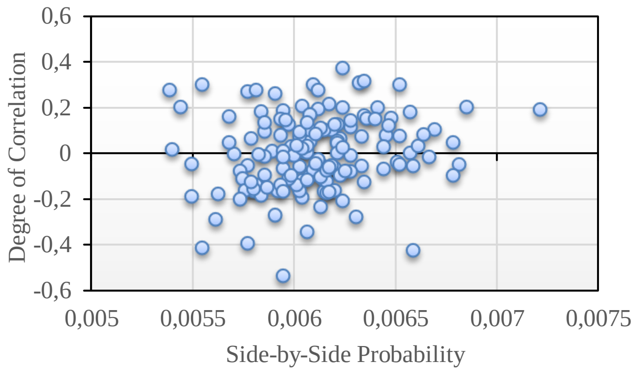

Figure 8. Degree of correlation vs side-by-side probability- half of the 290 bridges (each point represents a bridge on I5 southbound).

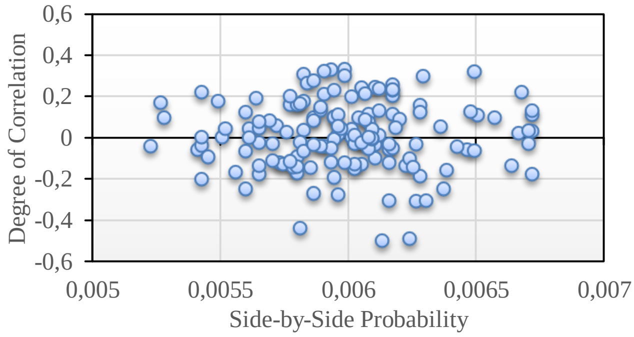

Figure 9. Degree of correlation vs side-by-side probability- other half of the 290 bridges.

A histogram of the correlation coefficients is shown in Figure 10 for all the bridges. In Figure 10 on average, the degree of correlation is near zero and appears to be normally distributed. The observed largest side-by-side probability was 0.0075. This value was smaller than the 1/15 value given by [18], for an ADTT of 5,000. And the degree of correlation at worst was less than 0.5. It was reported in [22] that, side-by-side probabilities ($P_{S/s}$) are, 0.008, 0.0016 and 0.0001578 for ADTTs of 5,000, 1,000 and 100, respectively.

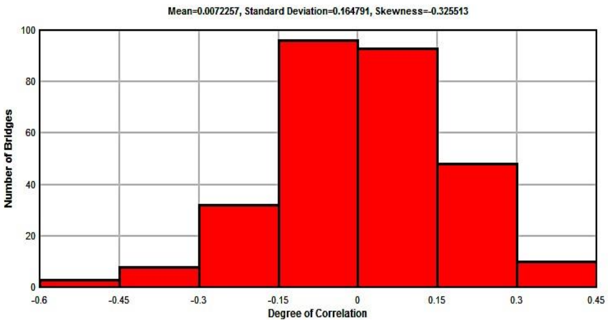

Figure 10. Histogram for degree of correlation from Monte Carlo simulations.

3. LANE LOAD STATISTICS

In this section lane load parameters are generated considering the Monte Carlo simulations defined above. Three degrees of correlation between the trucks loads in two adjacent lanes was considered in [18]. These correlations were; no correlation (ρ=0), partial correlation (ρ=0.5) and full correlation (ρ=1). Assumptions given in [18] were the following; every 15th truck is on the bridge is simultaneously with another truck (side-by-side). It was assumed in [22] that, for each simultaneous occurrence every 10th time the two trucks are partially correlated and every 30th time the two trucks are fully correlated with regard to weight. To be conservative in the two lane-loaded moment and shear calculations, the degrees of correlation defined in [22] were implemented in this study. The lane load parameters that were obtained for two lane bridges in this paper correspond to ADTT=5,000 (truck traffic in two lanes in one direction). Lane load parameters for Woodburn NB are presented in Table 2. The total number of occurrences, N, expected in the time period, T, is determined as:

$$N = T\ (ADTT)\ (365) \qquad (13)$$

here, T is the time period (5 years) and ADTT is 5,000 for Woodburn NB site. The number of events for lane 1 (L_1) with ρ=0, is expressed as:

$$N_{r=0} = N\ P_{S/S} \qquad (14)$$

where $P_{S/S}$ is the side-by-side probability 1/15. The number of events for lane 1 (L_1) with ρ=0.5 is calculated as:

$$N_{r=0.5} = N\ P_{S/S}\ (1/10) \qquad (15)$$

in which 1/10 value comes from every 10th time trucks are partially correlated. For the fully correlated case the number of events in lane 1 can be written as:

$$N_{r=1} = N\ P_{S/S}(1/30) \qquad (16)$$

in which 1/30 corresponds to every 30th time trucks on both lanes are fully correlated (both heavy trucks). The parameters for lane 2 are calculated such that when no correlation exists between the trucks the truck in lane 2 corresponds to the average truck. For the partially correlated case ρ=0.5, N in lane 2 can be determined as:

$$N_{r=0.5,L_2} = N_{r=0.5}\ P_{S/S}\ (1/10) \qquad (17)$$

For fully correlated case ρ=1, N in lane 2 can be written as:

$$N_{r=1,L_2} = N_{r=1} \qquad (18)$$

From the number of events, the z score can be determined for each of the lanes as:

$$\mathbf{z} = -F^{-1}(1/N) \qquad (19)$$

Where a z-score is the number of standard deviations from the mean of a data point.

Table 2. Lane Load Parameters for Two Lane Traffic Woodburn (ADTT=5,000).

Number of Lanes Loaded			N	z	T
One			9,125,000	5.18	5 Years
Two	ρ =0	L_1	608,333	4.65	4 Months
		L_2	1	0	Average
Two	ρ =0.5	L_1	60,833	4.15	12 Days
		L_2	405	2.81	1 day
Two	ρ=1	L_1	20,277	3.89	4 Days
		L_2	20,277	3.89	4 Days

(13)

In the study of [23] higher side-by-side probabilities that vary with ADTT (1/15, 1/100 and 1/1,000) were used, in this paper a side-by-side probability of 1/30 was used for all different ADTT levels. In [23], Np**P*s/s was considered as the number of events. However this paper used just Np as the number of events. With these new modifications the conclusions obtained from this study is given below.

4. CONCLUSION

In this study the side-by-side loading probabilities were found to be smaller than the ones that had been defined in the literature. These probabilities were also smaller than the ones presented in American Association of State Highway and Transportation Officials LRFD manuals. Degree-of-correlation of the side-by-side events were found to be normally distributed. The absolute maximum value of the degree of correlation was calculated as 0.54 that correspond to a side-by-side probability of 0.006. The smallest side-by-side probability was obtained as 0.0052. Maximum side-by-side event number on the corresponding bridges was found as 67. Highest z score was obtained for the one lane loaded case with 5 year time period and the lowest z score was found in two lane loaded case with a time period of one day. It was also found that, the bridge span lengths that ranged from 1.22 m to 567 m did not have a strong influence on the number of side-by-side events.

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APPENDIX

Table A-1 Bridges on I-5 Southbound (Lengths are given in feet)

Highway	MP	Bridge Name	Length
1	282.8	Champoeg Creek, Park Rd (Park Br)	220
1	4.61	Hwy 1 over Hwy 1 Frontage Road	136
1	5.36	Hwy 1 SB over Hwy 273	234
1	10.34	Hwy 1 over Neil Creek Rd	75
1	11.93	CORP over Hwy 1 (Mistletoe)	146
1	13.2	Hwy 1 SB over Crowson Rd	150
1	14.77	E Main St over Hwy 1	385
1	14.96	Bear Creek, Hwy 1 SB at MP 14.96	200
1	16.7	Mountain Ave over Hwy 1	259
1	17.29	Hwy 1 SB over Eagle Mill Rd	227
1	18.56	Butler Creek Rd over Hwy 1	277
1	21.92	Suncrest Rd over Hwy 1	275
1	22.42	Bear Creek, Hwy 1 SB at MP 22.42	285
1	23.07	Bear Creek, Hwy 1 SB at MP 23.07	285
1	27.09	Bear Creek, Hwy 1 SB at MP 27.09	315
1	27.2	Monotube Sign Cantilever Hwy 001 at MP 27.20	33
1	28.66	Medford Viaduct, Hwy 1	878
1	29.64	Hwy 1 over McAndrews Rd	164
1	30.69	Bear Creek, Hwy 1 SB at MP 30.69	206
1	33.85	Upton Rd over Hwy 1	218
1	34.28	Griffin Creek, Hwy 1	24
1	35.24	Jackson Creek, Hwy 1	30
1	36.09	Hwy 1 SB over CORP (Seven Oaks)	344
1	36.64	Tolo Road over Hwy 1	184
1	38.73	Hwy 1 over Foley Lane Frontage Rd	83
1	43.08	Hwy 1 over Galls Creek Front Rd Conn	31