Forth Estuary Transport Authority
Forth Road Bridge



2010 Bridge Specific Assessment Live Loading

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CONTENTS

1 INTRODUCTION

W.A. Fairhurst & Partners (Fairhurst) were appointed by the Forth Estuary Transport Authority (FETA) in 2010 to calculate the current Bridge Specific Assessment Live Loading (BSALL) for the suspended structure of the Forth Road Bridge.

This report describes the derivation of a BSALL based on traffic survey data recorded in September 2010. The report recommends a current 2010 BSALL for the suspended structure and details the principle variables adopted.

Previous BSALL's have been derived by Fairhurst based on traffic survey data recorded in 2002, 2005 and 2006. The 2010 BSALL has been compared to the previous loading curves derived for the bridge and commentary is provided on the changes in the derived loading.

2 TRAFFIC SURVEY DATA

2.1 Data Collection

FETA have installed a Weigh In Motion (WIM) system to the south end of the Forth Road Bridge. The system is the HI-TRAC 100 System by TDC Systems Ltd and is based on piezo electric sensors and inductive loops. At the installation all vehicles which pass of the bridge are measured. The carriageway configuration at the WIM installation is two northbound lanes and two southbound lanes.

The following key data is recorded for each vehicle:

- Vehicle speed.
- Vehicle classification.
- Gross vehicle weight.
- The individual axle weight and spacing of axles
- Vehicle arrival time.
- Lane occupied.
- Direction.

2.2 Period of Data Selected

The 2010 BSALL has been derived from analysis of a three week period of continuous traffic data provided by FETA for the period Wednesday 01 September to Monday 20 September 2010. Data has been taken from the month of September consistent with previous BSALL derivations.

3 ANALYSIS

The purpose of the analysis was to calculate the characteristic Bridge Specific Assessment Live Loading (BSALL) curve for the bridge. This is defined in the Department of Transport Standard BD 50/92 as having a 5% probability of occurrence in a period of 120 years.

3.1 Assumptions and Loaded Lengths

The assumptions made in the analysis of the traffic data and derivation of the BSALL are detailed below. These assumptions are based on those adopted in the derivation of the previous BSALL's which were considered appropriate to the analysis described in this report.

(i) By analysing a continuous three week traffic survey of vehicles crossing the bridge it is possible to evaluate the loading on selected loaded lengths, which would occur in the event that the traffic is constrained to cross the bridge in convoy.

(ii) The loading resulting from vehicles moving at normal traffic speeds in free flow conditions is generally too low to make a significant contribution to the design loads. The traffic flow is generally free flowing unless constricted by an incident. In undertaking the analysis, the traffic has been assumed to be unaffected by constraints outwith the suspended structure which have potential to cause jams.

(iii) The loadings refer to the base year (2010) traffic only with no allowance for traffic growth.

(iv) The three-week sample has been assumed to be representative of general traffic crossing the bridge.

(v) The derived loadings do not include any allowance for the simultaneous application of HA knife-edge load. HA knife edge load has a small effect on the global behaviour of the structure at the longer loaded lengths considered in the assessment of the Forth Road Bridge.

(vi) Dynamic impact loads are not significant at loaded lengths greater than 50 metres and therefore have not been considered.

(vii) Lateral bunching which would result in three lanes of traffic compressed together laterally to occupy two traffic lanes does not occur at loaded lengths greater than 50 metres and therefore has not been considered.

(viii) The BSALL has been calculated for loaded lengths 100m and greater.

The derivation of the BSALL was based on the formation of queues that form the critical loaded lengths for the main structural elements of the suspended structure. These are as follows:

- Lengths to define the characteristic loading curve: 100m, 200m and 300m.
- Length of side span: 408m.
- Length of main span: 1006m.

- Length of side span and main span: 1414m.
- Length of full bridge: 1823m.

In total 1,488,676 vehicles were recorded as crossing the bridge, during the three week period analysed.

3.2 Data Analysis

As stated previously, only stationary or slow moving traffic produces a significant loading, and therefore the initial part of the analysis involved taking the free flow traffic data and using it to simulate a queuing situation. This required assumptions to be made about vehicle length, vehicle spacing, queue duration and lane switching to simulate vehicle behaviour as they joined the queue.

Vehicle lengths were calculated on the following basis:

- Axle spacing measured as part of the survey.
- Axle to bumper length estimated according to vehicle classification and from results of similar analyses undertaken by Fairhurst. These dimensions have been set equal to those derived for the previous BSALL analyses for the Forth Road Bridge.
- The spacing between vehicles in a queue was assumed to be a constant 1.5m. This figure is unchanged from that adopted in the previous analysis. Previous work has confirmed that the analysis is not sensitive to this factor.

The stationary or slow moving traffic queue was formed by computer simulation. The simulation assumed that a queue formed in the following manner:

- An incident was assumed to occur in one carriageway causing both lanes of traffic to queue.
- Traffic was assumed to stay in lane until the length of one queue was 50m greater than the other at which point traffic would switch lanes to advance closer to the head of the queue.
- The build up of the two queues was simulated until both were greater than the loaded length under consideration. Queue weight and formation time for each lane was then recorded.

Following the initial queue formation the five vehicles at the head of the queue in each lane were released from the front of the queue. The two queues were then permitted to build up again until the queue length in both lanes was greater than the loaded length under consideration. New queue weight and formation times were then recorded. This process was repeated for each carriageway and for all vehicles in the three-week survey.

The time taken for a queue to form is dependent upon the density of traffic crossing the bridge. A maximum queue formation time was originally set in the analysis at 30 minutes and all queues that took longer than this time to form were disregarded. This approach is intended to avoid the incorporation of unrealistic queues in the derivation of the BSALL.

The limit of 30 minutes on the queue formation time has been based on FETA's procedures which dictate targeted times for the clearance of an incident. A limit of 30 minutes was also adopted in the derivation of previous BSALL. However discussions with FETA have indicated that this period can be exceeded when the removal of larger vehicles is undertaken. Therefore a sensitivity study was carried out to determine the effects of queue formation time on the calculated loading. Details of the study are provided in Section 3.6.1 of this report.

3.3 Calculation of the Characteristic Loading for a Single Lane

The analysis indicated that the weights of the traffic queues in the northbound direction would be higher than in the southbound direction for the range of loaded lengths considered. Therefore the calculation of the characteristic load for a single lane has been based upon the data for the northbound direction.

The calculation of the characteristic load, over the range of loaded lengths considered for the northbound direction, is tabulated in Table 1 of Appendix B. The results are plotted in Figures 2. Also plotted in Figure 2, for comparison, are the nominal uniformly distributed loads from the following:

- 2006 recommended BSALL,
- BD 37/01 the current design loading,
- BD 50/92 the current 40 tonnes assessment loading for long span bridges.
- BS 153: 1954 the original design loading.

The methodology adopted in calculation of the BSALL is summarised below. The calculations are based on a normal distribution of the data which previous work has indicated is satisfactory for the longer loaded lengths considered.

- The data manipulated in the manner described in Section 3.2 produces a given number of individual queues in the northbound direction over the three week survey.
- The number of simulated queues is factored to give an equivalent amount in a single year. However this assumes that all vehicles which will cross the bridge are in convoy. The actual number of vehicles which will be involved in a queuing situation will be dependant on the number of incidents at the bridge. The percentage of vehicles involved in queuing can be estimated and we have based the calculations on a figure of 1.93%. Details of the calculation of this figure and a sensitivity study in relation to this factor are provided in Section 3.6.2.
- The individual queue events are analysed to calculate the mean queue weight and the standard deviation from the mean based on a normal distribution.
- The characteristic loading is calculated from the mean queue weight and the standard deviation adjusted by the factor r, which represents the standard deviation of the tail probability for a normal distribution. The standard deviation of the tail probability is derived from published tables. The calculation of the tail probability takes account of the probability the characteristic loading shall have a 5% chance of being exceeded in 120 years.
- The nominal BSALL load is taken as the characteristic value divided by a factor of 1.2 (ref. to BD 50/92 and TRRL Contractor Report 16).

3.4 Calculation of the Characteristic Loading for the Lane adjacent to the Slow Lane

The characteristic loading for the lane adjacent to the slow lane (lane 2) was calculated in a manner similar that described in Section 3.3. The results are given in Table 2 of Appendix B and show an average lane factor of 0.44.

The calculated average lane factor is lower than the figure of 0.67 reported in TRRL Contractors Report 16 and specified in BD 37/01 and the figure of 1.0 specified in BS 153:1954 for the original design. The loading specified in TRRL Contractors Report 16 and BD 37/01 attempts to predict all possible loading scenarios for all common bridge configurations. This loading was derived from analysis of predicted traffic queues for the United Kingdom based on traffic surveys undertaken at a number of locations. The loading and factors adopted in BS 153:1954 was based on an assumed traffic distribution of heavy goods vehicles which at longer loaded lengths were interspersed with cars.

Considering the above comments, the adoption of a value of 0.67 for the second lane would allow for scenarios which may occur but are not reflected in the sampled traffic data. Therefore we have recommended a lane factor of 0.67 for the second lane.

3.5 Calculation of the coincident loading on the secondary carriageway

Queuing is assumed to occur only in response to specific incidents. Therefore in practice it would not be unreasonable to assume that queuing is unlikely to develop on the second carriageway concurrent with queuing on the first carriageway. However there are indications that incidents on both lanes of a dual carriageway are linked. This may be due to the traffic slowing down and being distracted in the second carriageway by an incident in the first carriageway, alternatively this may also occur as a result of poor weather conditions.

Based on consideration of the above, the characteristic loading in the southbound carriageway was assumed to equal the mean traffic queue loading that was simulated during the three week survey period. The figures for the southbound slow and fast lanes (lanes 3 and 4) with lane factors relative to the southbound slow lane are given in Table 3.

The calculated lane factors for the southbound carriageway presented in Table 3 are lower than the second carriageway lane factors quoted in the following documents:

- TRRL Contractors Report 16 which quotes a figure of 0.5 for each lane,
- BD 37/01 and BD 50/92 which quotes a figure of 0.6,
- BS 153: 1954 which quotes a figure of 0.33 for each lane.

The lowest factor quoted above is that used in BS 153 of 0.33. This factor was derived from practical experience and was adopted in the original design of the Forth Road Bridge. The calculated lane factors are lower than 0.33. Therefore to remain consistent with the original design we recommend that a value of 0.33 is adopted for lanes 3 and 4.

3.6 Sensitivity Study

A study was undertaken to establish the sensitivity of the analysis and data manipulation to variations in the queue formation time and the percentage of vehicles involved in queuing.

3.5.1 Queue Formation Time

The computer simulation of the traffic queues has been undertaken for an alternative queue formation time limit of 60 minutes for the critical loaded lengths only. The findings of these analyses indicated that increasing the queue formation time increased the calculated loading by an average of 1.3%. The findings also indicated that the analysis becomes more sensitive to queue formation time at the longer loaded lengths above 408m.

We are of the opinion that the 30 minutes adopted in the derivation is a reasonable estimate based on FETA procedures for clearing incidents. Occasional instances where the time to clear the incident exceeds 30 minutes do occur the use of lane factors greater than calculated for both Lane 2 and Lane 3 / 4 loading will more than cover the small increases in potential loading.

3.5.2 Percentage of Vehicles involved in Queuing

The previous work undertaken to derive the BSALL for the Forth Road Bridge since 2002 examined the sensitivity of the analysis to the assumed percentage of vehicles involved in queuing. The methodology adopted previously demonstrated that the analysis was not particularly sensitive to this factor. For the purposes of the 2010 BSALL a similar study has been undertaken as follows.

The calculation of the percentage of vehicles involved in queuing was undertaken using the methods detailed in the 2002 report. A comparison of the characteristic loading determined by the different methods showed that the calculated loading varied by +/-2% from the average loading derived from the three methods. These results confirmed previous findings in relation to the sensitivity of the analysis to this factor.

Based on above findings the recommended BSALL was calculated on the basis of the number of vehicles involved in queuing being 1.93% as adopted for the previous BSALL analyses.

3.6 Commentary and Comparison with the Previous BSALL

3.6.1 Difference in Carriageway Loading

As stated in Section 3.3 the analysis indicated that the northbound carriageway loading was greater than the southbound.

The difference in carriageway loading since we derived the 2002 BSALL has varied. The 2005 and 2006 BSALL's showed significant differences in carriageway loading with the Southbound direction being greatest. The 2002 BSALL found both carriageway loadings to be of a similar magnitude, southbound being marginally more critical.

Comparing the various BSALL's which have been derived is complicated by the large volume of data and the number of different vehicle classifications to consider. Attempts to identify trends are further complicated by the changes in the local road network around the Forth Estuary which have taken place since 2002 and in particular;

- Construction of the M9 spur on the southern side of the bridge.
- Construction of the new crossing near Kincardine.
- Removal of the tolls on the northbound carriageway.

However we have found that reviewing the changes in volume and total tonnage of vehicles classified as HGV's by FETA will generally indicate similar patterns to the calculated loading. Since 2002 the following trends in total tonnage of HGV traffic have been evident.

- 2002 – The difference in total weight of HGV between the north and south bound directions was approximately 9%. Southbound being greater.
- 2005 – The difference in total weight of HGV between north and south bound directions had significantly increased to approximately 29%. Southbound still being greater. The total tonnage of HGV had increased significantly southbound by approximately 11% with a reduction of 7% northbound.
- 2006 – The difference in total weight of HGV between north and south bound directions had increased approximately 34%. Southbound was still greater. The total tonnage of HGV had increased southbound by approximately 7% and northbound by approximately 3%.
- 2010 – The difference in total weight of HGV between north and south bound directions was significantly reduced to approximately 10%. However the greater tonnage is now in the northbound direction at a level comparable to the southbound in 2006. The total tonnage in the southbound direction has reduced by approximately 10% from 2006.

The change in total tonnage in each carriageway appears to reflect the changes found in the critical carriageway for the BSALL loading. The total weight of HGV's in each direction each year the BSALL has been calculated is shown in the following table.

Traffic Direction	**Total HGV Weight in Tonnes / Year**			
	2002	**2005**	**2006**	**2010**
Southbound	854,055	946,582	1,011,710	914,601
Northbound	785,175	731,398	756,605	1,010,055
Ratio South/North	1.09	1.29	1.34	0.91

Total Tonnage of HGV Traffic each Direction

3.6.2 Comparison of 2006 and 2010 Recommended BSALL for a 120 year return period

A comparison of the recommended BSALL, based on a 5% probability of occurrence in 120 years, from 2006 and 2010 has identified the following.

- The 2010 BSALL lane 1 loading is on average 4% greater than that derived in 2006. The percentage varies with loaded length with a peak of 6% at 408m and a minimum of 3% at 1823m.
- The critical lane 1 load has changed from southbound in 2006 to northbound in 2010.
- The critical carriageway load has increased by approximately 5% from 2006.
- The critical carriageway loading has changed to northbound from southbound in 2006.

For comparison purposes the 2010 BSALL has been plotted with the 2002, 2005 and 2006 BSALL's in separate Figures 3 and 4 of Appendix A for the Bridge Total and Lane 1 loading respectively.

4 CONCLUSIONS

A 2010 Bridge Specific Assessment Live Loading has been derived based on specific parameters summarised later in this section. The recommended loading based on a 120 year return period and lane factors are provided in the following table.

LOADED LENGTH (m)	2010 LANE 1 (kN/m)	LANE 2 FACTOR	LANE 3 FACTOR	LANE 4 FACTOR
100	21.11	0.67	0.33	0.33
200	17.63	0.67	0.33	0.33
300	16.13	0.67	0.33	0.33
408	15.20	0.67	0.33	0.33
1006	13.41	0.67	0.33	0.33
1414	12.96	0.67	0.33	0.33
1823	12.71	0.67	0.33	0.33

Summary of recommended 2010 Bridge Specific Assessment Live Loading (Nominal Values for a 120 year return period)

Previous BSALL derivations have varied by approximately 1%. However the 2010 BSALL has increased from that derived from 2006 traffic data by an average of 4%. This increase is in conjunction with a change in critical carriageway from south to north. The change in loading is generally mirrored by the changes in total weight of HGV traffic crossing the bridge in each carriageway from 2006 to 2010. The data suggests that an increased tonnage of HGV traffic is using the bridge in the northbound direction since the tolls were removed.

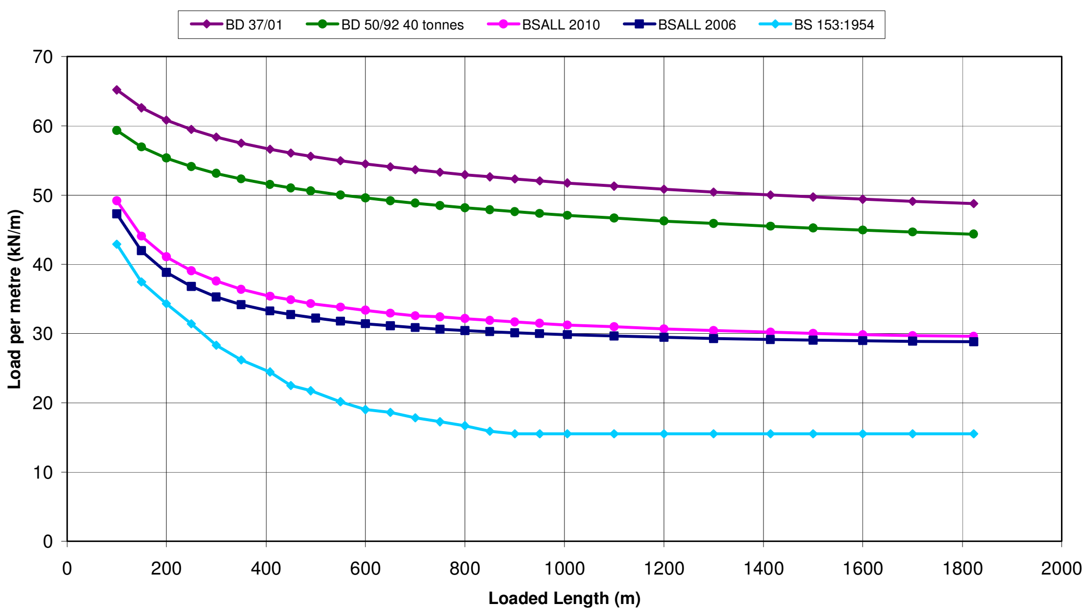
We would recommend that the BSALL is reviewed in two years time in accordance with the recommendations of BD 50/92.

The recommended 2010 Bridge Specific Assessment Live Loading has been based upon the parameters detailed below. These parameters have been chosen specific to the conditions at the Forth Road Bridge site.

- The maximum queue formation time was set at 30 minutes and vehicle spacing at 1.5m.
- The percentage of vehicles involved in queuing was taken as 1.93%.
- Values for the principal lanes, lane 1 and 2, have been based upon the results for the northbound direction, which are higher than those for the southbound direction. Lane 3 and 4 have been based upon results for the southbound carriageway, as they are considered to be coexistent with lane 1 and 2.

- The lane 1 loading has been taken as that loading which has a 5% chance of being exceeded in 120 years. This loading is known as the characteristic loading.
- The lane 2 factor has been taken 0.67. This is higher than the calculated lane 2 loading. However this is consistent with the factors adopted in current design standards which attempt to predict all possible loading scenarios.
- The lane factors for loading in lanes 3 and 4 have been set at 0.33 consistent with the original design loading from BS 153: 1954. This has been shown to be higher than the mean queue traffic loading simulated during the three week survey period which allows for a conservative approach on this subjective variable.

Total nominal bridge loadings for the current bridge design loading BD 37/01, original design values from BS 153 and the recommended Bridge Specific Assessment Live Loading as calculated, are plotted on the following chart.



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5 REFERENCES

1. Contractor Report 16: Interim Design Standard – Long span bridge loading. Transport and Road Research Laboratory, Department of Transport, May 1986.

2. Leaflet LF 687 Issue 3 – Vehicle Category Listing for the U.K. Core Census. Transport and Road Research Laboratory, March 1983.

3. Design Manual for Roads and Bridges: BD 37/01 Loads for Highway Bridges. Highways Agency, August 2001.

4. Design Manual for Roads and Bridges: BD 50/92 Technical Requirements for the Assessment and Strengthening Programme for Highway Structures Stage 3 – Long Span Bridges. Highways Agency, December 1992.

5. BS 153: British Standard Specification for Steel Girder Bridges Part 3A: 1954. British Standards Institute, December1954.

6. Bridge Specific Assessment Live Loading Report by W.A. Fairhurst & Partners, Rev. 1 dated 14 March 04.

APPENDIX A – FIGURES

Figure 1 : Recommended Assessment Loading (Nominal) - Bridge Total

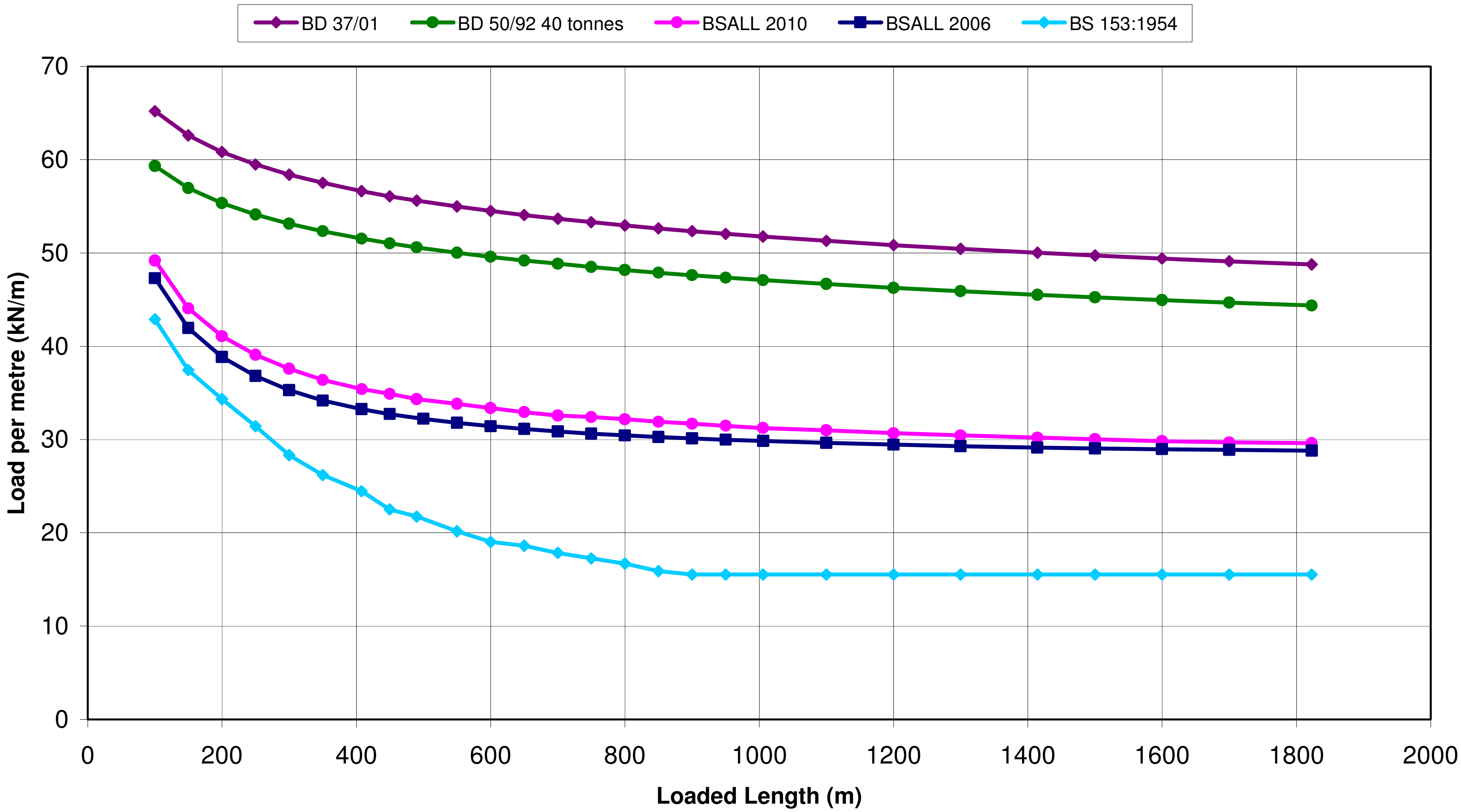

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Figure 2 : Recommended Assessment Loading (Nominal) - Lane 1

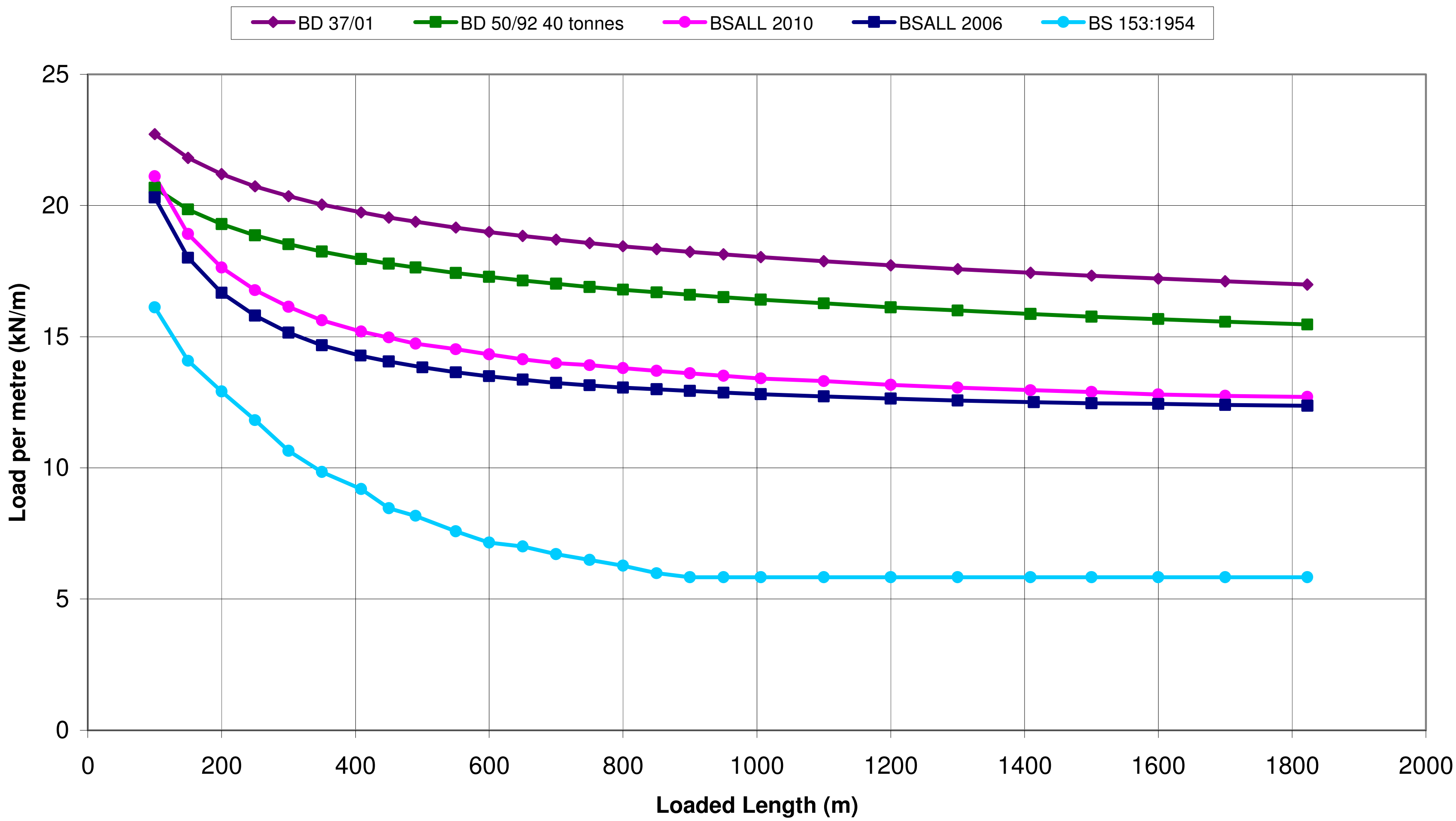


Figure 3 : Comparison with Previous Recommended Assessment Loadings (Nominal) - Bridge Total

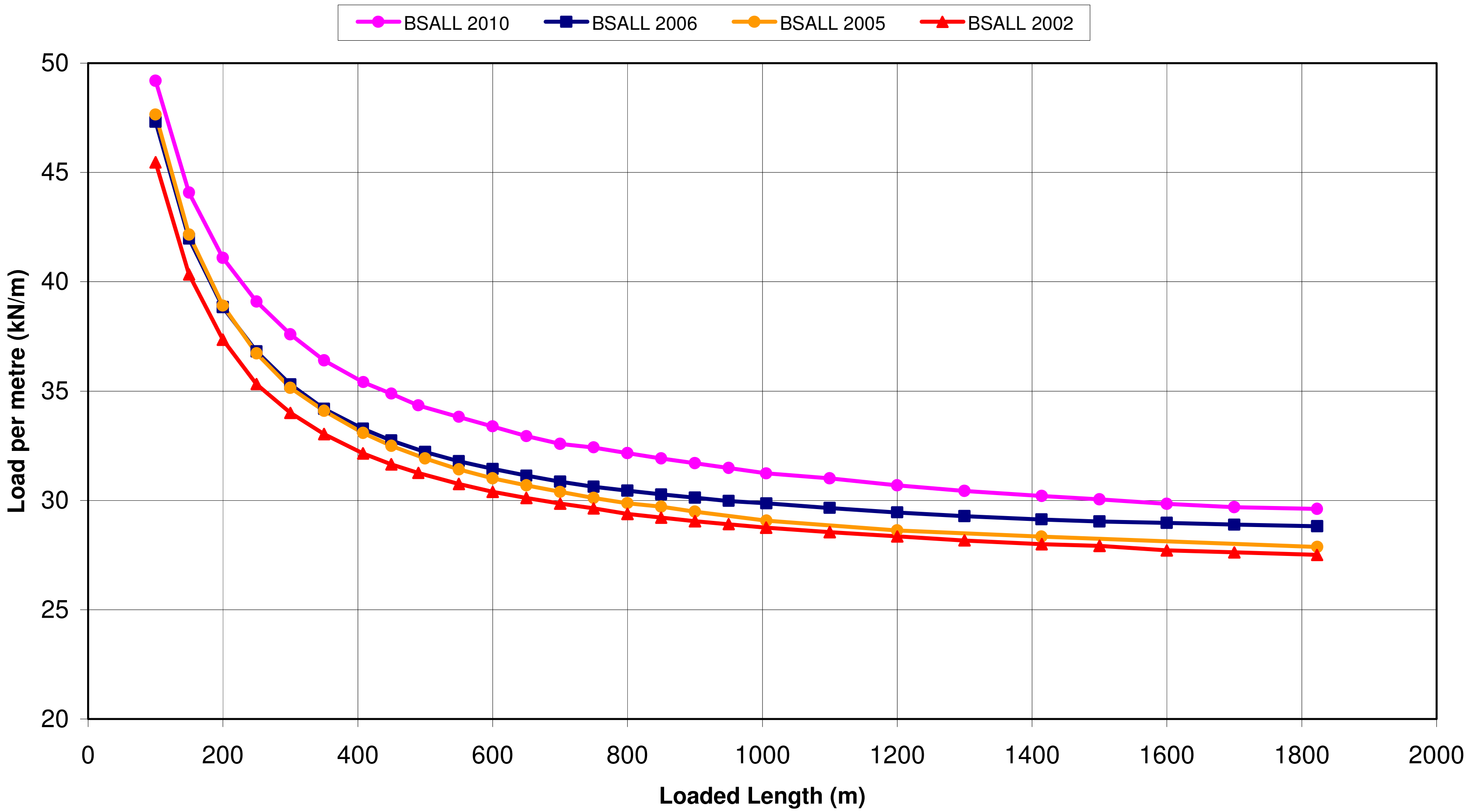
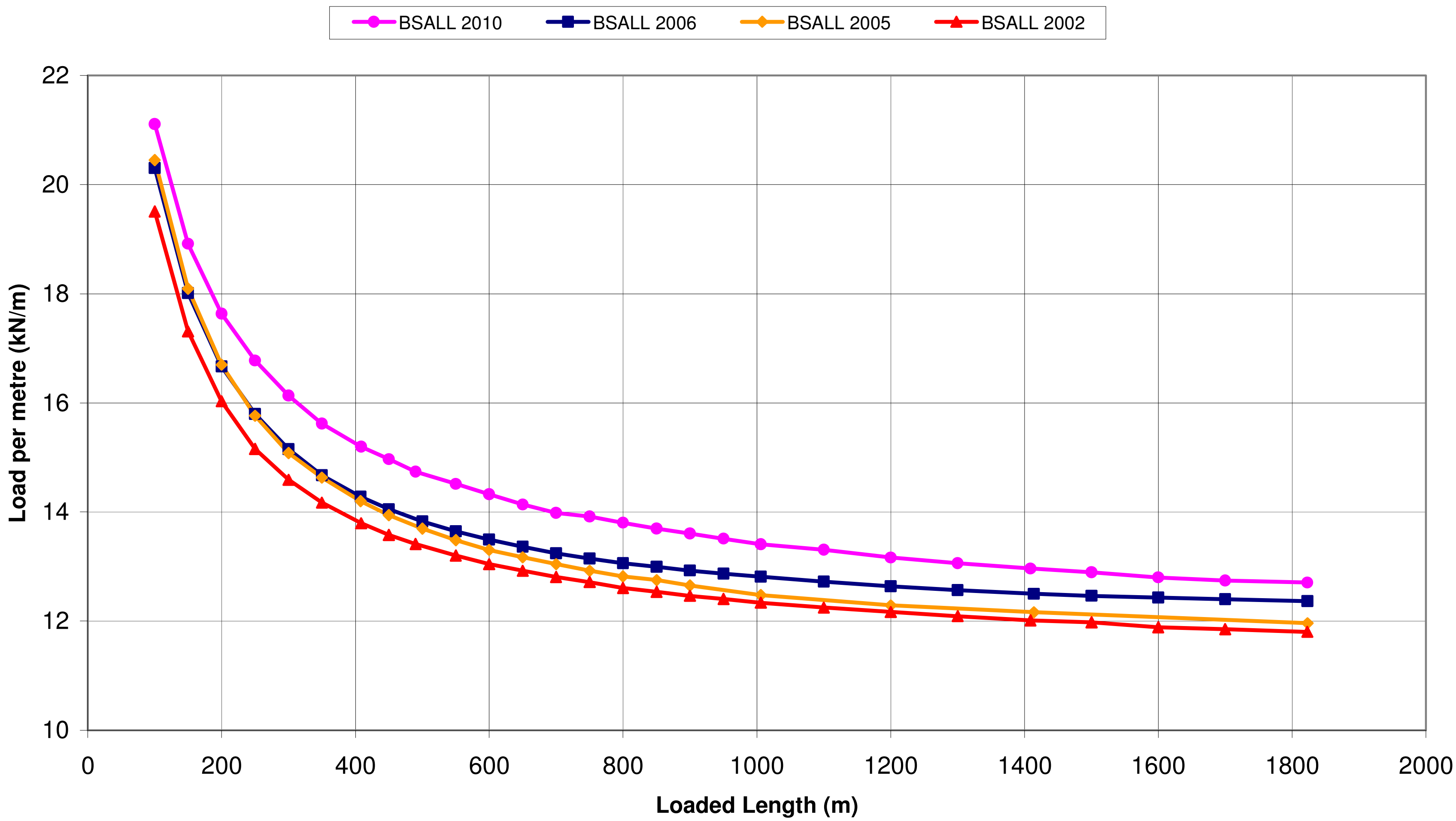


Figure 4 : Comparison with Previous Recommended Assessment Loadings (Nominal) - Lane 1



APPENDIX B – TABLES

Table 1 : Calculation of the assessment loading for the northbound slow lane.

Table 2 : Calculation of the assessment loading for the northbound fast lane.

Table 3 : Mean traffic queue weights for the southbound slow and fast lanes.

LEGEND

P (tail probability) and 'r' :

The calculation of P (tail probability) takes account of the probability that the derived loading has a 5% chance of being exceeded in 120 years. The factor 'r' is the number of standard deviations from the mean corresponding to the tail probability.

Mean and 's' :

The mean of the square root of each of the individual queue weights obtained from the analysed traffic data. 's' is the standard deviation of the mean.

NBSL :

Northbound Slow lane.

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Table 1 Calculation for Northbound slow lane

Loaded Length (m)	Survey No. of events	Average No. of vehicles in queue	No. of events per year	No. of events in 120 years	No. of vehicles involved in Queues (1.93%)	P Probability	r	mean	s	Characteristic Loading kN/m	Nominal Loading kN/m
100	72406	15	1258485	151018229	2914652	1.72E-08	5.518	20.31	5.53	25.33	21.11
200	72249	28	1255756	150690771	2908332	1.72E-08	5.518	20.54	4.70	21.16	17.63
300	71759	42	1247240	149668771	2888607	1.73E-08	5.517	20.60	4.32	19.36	16.13
408	71156	58	1236759	148411086	2864334	1.75E-08	5.515	20.62	4.08	18.24	15.20
1006	68634	142	1192924	143150914	2762813	1.81E-08	5.509	20.67	3.60	16.09	13.41
1414	66385	199	1153835	138460143	2672281	1.87E-08	5.503	20.73	3.47	15.55	12.96
1823	63930	256	1111164	133339714	2573456	1.94E-08	5.496	20.80	3.39	15.25	12.71

Table 2 Calculation for Northbound fast lane

Loaded Length (m)	Survey No. of events	Average No. of vehicles in queue	No. of events per year	No. of events in 120 years	No. of vehicles involved in Queues (1.93%)	P Probability	r	mean	s	Characteristic Loading kN/m	Nominal Loading kN/m
100	77673	15	1350031	162003686	3126671	1.599E-08	5.530	15.87	3.45	11.98	9.98
200	77514	30	1347267	161672057	3120271	1.602E-08	5.530	15.97	2.95	10.22	8.52
300	77005	45	1338420	160610429	3099781	1.613E-08	5.529	15.96	2.64	9.16	7.63
408	76384	61	1327627	159315200	3074783	1.626E-08	5.527	15.93	2.40	8.36	6.97
1006	73790	151	1282540	153904857	2970364	1.683E-08	5.521	15.86	1.89	6.78	5.65
1414	71449	212	1241852	149022200	2876128	1.738E-08	5.516	15.83	1.73	6.31	5.26
1823	68863	274	1196905	143628543	2772031	1.804E-08	5.509	15.82	1.64	6.06	5.05

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Table 3 : Southbound mean queue traffic weights.

Southbound Slowlane Characteristic Loading kN/m	Loaded Length (m)	Southbound Slowlane mean queue kg/m	kN/m	No. Events	Southbound Fastlane mean queue kg/m	kN/m	No. Events	Average kN/m	Ratio of the Average to NBSL Characteristic Loading	Ratio of South Slow Lane to NBSL Characteristic Loading	Ratio of South Fast Lane to NBSL Characteristic Loading
25.33	100	372	3.648	70055	299	2.932	77160	3.290	0.1299	0.1440	0.1157
21.16	200	372	3.648	69668	299	2.932	76777	3.290	0.1555	0.1724	0.1386
19.36	300	373	3.658	69371	298	2.922	76460	3.290	0.1699	0.1889	0.1510
18.24	408	373	3.658	69072	298	2.922	76160	3.290	0.1804	0.2006	0.1603
16.09	1006	373	3.658	66958	297	2.913	73935	3.285	0.2042	0.2274	0.1811
15.55	1414	374	3.668	64576	297	2.913	71449	3.290	0.2115	0.2358	0.1873
15.25	1823	375	3.678	62331	297	2.913	69018	3.295	0.2161	0.2412	0.1910

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