Flint & Neill Partnership
Consulting Engineers

HIGHWAYS AGENCY

**Derivation of the UK National Annex to Clause 4.6:
Fatigue Load Models:
Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges**

REPORT

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**Report on the Derivation of the UK National Annex to Clause 4.6: Fatigue Load
Models: Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges**

1   INTRODUCTION

The UK Highways Agency is tasked with developing the National Annex to BS EN 1991-
2:2003. The commission defined the tasks as follows:

*The scope of work is to consider clause 4.6 Fatigue load models of BS EN 1991-2:2003
Traffic Loads on Bridges and to propose for this clause the National Determined Parameters
and any non-contradictory complementary information in the UK National Annex, based on
the Fatigue load model produced recently for the Highways Agency.*

*For information only, the Highways Agency provided the list of sub-clauses which must be
considered as given in the table below:-*

BS EN 1991-2:2003 Clause No.	Guidance to be included in the UK National Annex
4.6.1(2) Note 2(c) and 2(e)	*Advise on the use of Fatigue Load Models considering the simultaneous presence of several lorries on the bridge*
4.6.1(2) Note 4	*Modifications to Fatigue Load Models 1, 2 and 3 for non-motorway traffic*
4.6.1(3) Note 1	*Consider if traffic categories defined in Table 4.5 need to be revised for UK conditions, and if so recommend appropriate values.*
4.6.1(6)	*If appropriate, define an additional amplification factor (fatigue) for sections near expansion joints*
4.6.2(1)	*Adjustment of Fatigue Load Model 1. Consider if this should defined for a Particular Project or a value recommended in NA.*
4.6.4(3)	*Define adjustments for Fatigue Load Model 3*
4.6.5(1) Note 2	*Define road traffic characteristics for the use of Fatigue Load Model 4, especially if Table 4.5 is to be revised for UK*
4.6.6(1)	*Specify the use of Fatigue Load Model 5 based on recorded traffic data together with the guidance given in Annex B.*

*The deliverable will be a report giving the appropriate text, which can be directly inserted
into the National Annex . The necessary background for each of the above clauses shall be
included.*

Flint & Neill Partnership (FNP) was commissioned to draft clauses for fatigue loading in the
National Annex. This report describes the stages of the FNP task, and provides a proposed
text for the National Annex. It also identifies some inconsistencies in the parts of the BS EN
document that describe where National Annex material may be provided.

2   THE FATIGUE MODELS

Five different highway traffic loading models are provided in BS EN 1991-2:2003 for fatigue design purposes. These are intended to provide different levels of sophistication and economy.

The Forward to BS EN 1991-2:2003 also defines which of its clauses can be modified in the National Annex.

Fatigue Models 1, 2 and 3 are used to provide stress ranges and are not used to provide counts of stress ranges. In the case of many intermediate span bridges, these may amount to the same thing. However, where influence lines have several peak or trough values, or where they are short enough to be sensitive to individual axles, the product of vehicle numbers and the associated numbers of extreme stress ranges will not provide an accurate model of stress cycle counts.

Fatigue Models 1 and 2 are to be used to check whether fatigue life can be considered to be unlimited. Therefore, Models 1 and 2 can only provide safe indications of unlimited life if they are conservative. According to **4.6.1(2) Note 4**, the magnitude of Fatigue Load Models 1 and 2 may be adjusted in the National Annex "when considering other categories of traffic", whereas Note 3 tells us that models 1 to 3 are appropriate for typical heavy traffic on European main roads and motorways. Neither **4.6.2** (which describes Fatigue Load Model 1) nor **4.6.3** (which describes Fatigue Load Model 2) mention this, and nor does this permission appear in the list of clauses in which National choice is permitted.

Model 1 is closely based on the static design load model LM1, and Model 2 is a description of a set of idealised "frequent" European lorries.

Model 3 is to be used for direct verification of designs, taking account of bridge dimensions and traffic volume. Model 3 can only provide a realistic indication of expected life if particular procedures are followed. The fact that Model 3 is only to be used to establish maximum and minimum stresses (**4.6.4(2)**) appears to conflict with the statement (**4.6.1(2) d)**) that it is intended for life assessment and not for confirmation of unlimited life. This conflict can be resolved if data are provided to allow damage effects from Model 3 to be related to damage from realistic traffic models. BS EN 1991-2:2003 states "The conditions of application of this model may be defined in the National Annex …". It describes how the axle loads might be altered, or additional vehicles might be imposed.

Fatigue model 4 comprises a description of a set of vehicles that is intended to produce the same amount of fatigue damage as a typical sample comprising matching numbers of heavy goods vehicles on European roads. This model is intended to be used in time-history analysis in association with a rainflow counting procedure to assemble stress cycle ranges for use in fatigue life assessment. BS EN 1991-2:2003 states "Other standard lorries and lorry percentages may be defined … in the National Annex". This allows us the freedom to entirely re-define Model 4 if we so choose.

Fatigue model 5 is to be developed for specific locations from realistic traffic data for the site. It describes the procedure of using site observations to assemble a traffic model for use

in time-history analysis and rainflow count analysis. We are free to define the conditions of use, and provide guidance for a complete specification and application of this model in the National Annex.

3   REPORT ON TASKS AS DEFINED BY THE HIGHWAYS AGENCY BRIEF

3.1   Task 1: "Advise on the use of fatigue load models considering presence of several vehicles on the bridge"

Models 1, 2 and 3 require the user to calculate maximum and minimum stresses, and to compare the stress range with the non-propagating stress range for the fatigue detail being considered. This is similar to the procedure defined in clause 8.2 of BS5400: Part 10: 1980. However, BS5400 compares the stress ranges with a range of different limiting stresses (Figure 8 of BS5400: Part 10:1980), and NOT with a single non-propagating stress. Thus, BS5400 inextricably links the load models to the assessment process in a manner that caters for the effects of simultaneous loading by several vehicles.

Models 2 and 3 represent particular vehicles. The effect of multiple vehicles relative to these models was investigated by taking a real traffic record, simulating its effects on a series of influence lines, and comparing the fatigue rainflow cycle counts produced by its individual vehicles crossing bridge influence lines one at a time with the effects of the actual record taking into account close following behaviour and simultaneous loading on adjacent traffic lanes.

Two influence lines were considered:

- Moment in the centre of a simply supported beam
- Bending over the central support of a beam with two equal spans

Flowing traffic was considered because there are typically many more flowing traffic events than stationary traffic events. Also, when heavy congestion occurs, dilution of heavy goods vehicles numbers by intermediate cars reduces numbers of lorry sequences.

3.1.1   Simply Supported Beam Mid Span Bending

Table 1 illustrates the relationship between the effects of flowing traffic in two lanes at a busy motorway site (Warrington, M6, 1990) and that of individual vehicles in lane 1 only. It is assumed that the detail is equally sensitive to loading in either lane. In this Table, a damage level of 1.00 represents that caused by all the Lane 1 vehicles, with damage assumed to be calculated by adding the cubes of all stress ranges caused by individual vehicles.

SPAN	LANE 1	LANE 2	LANE 1 + LANE 2	LANES 1+2	Lanes (1+2) (Lane1+Lane 2)
(1)	(2)	(3)	(4)	(5)	(6)
3	0.99	0.43	1.42	1.56	1.10
5	1.00	0.44	1.44	1.57	1.09
10	1.00	0.45	1.45	1.65	1.14
25	1.00	0.45	1.45	1.68	1.16
50	0.96	0.42	1.39	1.66	1.20
100	0.91	0.41	1.33	1.76	1.33
200	1.10	0.60	1.70	2.50	1.47

Table 1: Damage Relative To Individual Vehicles In Lane 1 Alone

Column (2) shows that close following vehicles in flowing traffic in the same traffic lane cause very little increase in fatigue damage for most influence line lengths, relative to assessing the effects of independent vehicle transits. There was actually some very small benefit at 100 m span, because the numbers of complete stress cycle ranges is reduced if a new vehicle arrives before the previous vehicle has left the bridge. At 200 m the damage due to close following vehicles was about 10% greater than that caused by individual vehicles, because some vehicle spacings were small enough relative to the span to cause larger stress cycles. This implies an average increase in stress cycle ranges of only about 3%, which is trivial compared with other assumptions. This increase is equivalent to factor "Y" described in clause C.4.3. in BS5400: Part 10: 1980, although Figure 11 shows that "Y" increases to 2.0 at 200 m (which appears to be over-conservative).

Column (3) shows that, at all except the longest spans, traffic in lane 2 caused about 45% of the damage of traffic in lane 1. Most of the difference is probably caused by the reduced numbers of lorries in lane 2 relative to lane 1. At the longest span, total lane 2 damage rose to 60% of lane 1, presumably because now there were enough close following vehicles to increase the extreme stress ranges. Thus the "Y" factor for lane 2 is about 0.60/0.45, or about 1.35.

Column (6) presents the ratios between Column (5) (the effect of simultaneous vehicles side by side in both traffic lanes) and the effect of adding independent damage from lane 1 to lane 2. This is equivalent to factor "Z" in BS5400, and implies that the "Z" parameter could be modelled by using about 1.15 up to 25 m, and then increasing with the logarithm of the span to 1.5 at 200 m. Compare "Z" in BS5400, which increases with the logarithm of span from unity at 3 m to 1.5 at 25 m, and remains at 1.5 thereafter.

On the basis of this limited study, it appears that Figure 11 in BS5400 provides a reasonable model for the fatigue effects of several vehicles on the same bridge.

Under congested traffic conditions, there will be larger numbers of additional stresses caused by the simultaneous presence of close following vehicles. Usually this should be offset to some extent by dilution effects caused by the large numbers of light vehicles present during the busiest traffic periods. The relatively high "Y" parameter provided by Figure 11 of BS5400: Part 10 will safely account for such effects.

3.1.2   *Bending over the centre support of a two-span beam*

Table 2 repeats Table 1 for the influence line for bending over the centre support of a two-span beam, which has two separate peak values. For spans over about 100 m, close following vehicles may often appear simultaneously close to both peaks, leading to a stress increase. The maximum "Y" parameter (represented by the value in column (2) at 200 m) is now 1.60, compared with the BS5400 value of 2.0. If the possibility of congested traffic is also included, this seems to justify Figure 11 in BS5400.

SPAN	LANE 1	LANE 2	LANE 1 + LANE 2	LANES 1+2	Lanes(1+2) (Lane1+Lane 2)
(1)	(2)	(3)	(4)	(5)	(6)
3	0.99	0.43	1.42	1.56	1.09
5	1.00	0.46	1.46	1.59	1.09
10	1.00	0.43	1.43	1.63	1.14
25	1.00	0.46	1.45	1.66	1.14
50	0.97	0.43	1.40	1.95	1.39
100	1.36	0.71	2.07	2.85	1.38
200	1.60	0.82	2.42	3.55	1.47

Table 2: Damage Relative To Individual Vehicles In Lane 1 Alone

The "Z" parameter in column (6) of Table 2 is very similar to that in Table 1.

3.1.3   *Conclusions:*

3.1.3.1   *Use of Model 1:*

If Model 1 is applied to two lanes that both have similar effects on a component stress, it may cause up to 67% more stress effect, or nearly 5 times as much damage, than when applied to a single lane. The maximum value required by columns (5) of Table 1 and Table 2 was 3.55 on damage, or about 1.5 on stress. Therefore, the use of Model 1 to represent side by side traffic is conservative in terms of stress in some cases. It is concluded that Model 1 requires no special modifications in the National Annex to cater for the presence of several vehicles on the bridge.

3.1.3.2   *Use of Model 2:*

Where influence lines have two (or more) pronounced peak values, a significant number of ranges of stress cycles may be increased. This can be seen in the value in Column 2 of Table 2 at 200 m length, where the damage due to multiple vehicles in one lane is 1.60 times that that due to one vehicle. That, however, implies only some $\sqrt[3]{1.60}$, or a 1.17 factor on stress. Therefore, Model 2 will be suitable for demonstrating unlimited life provided that we ensure that, if the influence line has two peaks, both peaks may be loaded. Therefore, two vehicles should be selected and run simultaneously, although we do not need both vehicles to provide the same stress. It is proposed to follow the proposal from the note under Model 3 (**4.6.4(2)**) that the stress range be calculated from the effects of two vehicles from Table 4.6, spaced at 40 m centre to centre. The first vehicle should be the most onerous of those listed in Table 4.6, and the second vehicle could be the lightest of those listed (i.e. the 2-axle rigid lorry).

If the individual vehicles in Model 2 were run side by side, they would cause 2 times the stress range and therefore up to 8 times the damage, whereas the maximum value in columns

(5) of Table 1 and Table 2 was 3.55 on damage, or about $(3.55)^{1/3}$, or 1.5, on stress. It is again proposed that, where a detail is equally sensitive to loading in two lanes, the stress range be calculated by adding the maximum stress range from a transit of the worst vehicle in lane 1 to that from the least onerous vehicle in lane 2.

3.1.3.3 Use of Model 3:

It is proposed that damage be assessed by calculating the damage caused by one lane's traffic, and applying correction factors to allow for enhanced stresses due to close following and due to side by side vehicles.

3.1.3.4 Use of Model 4:

Model 4 is to provide stress ranges and corresponding numbers of load cycles. A similar method is described under Clause 8.4 of BS5400: Part 10: 1980 "Damage calculation: vehicle spectrum method". Clause 8.4.2.1 of BS5400 says that account shall be taken of simultaneous presence of vehicles, but it provides no guidance on the method of doing so.

What cannot be gauged from Tables 1 or 2 is whether the additional damage cause by multiple vehicles is due to additional numbers of stress cycles, or magnitudes of stress ranges, or both. If we are to perform realistic Miner's rule summation, we need to know how to apply our spectrum.

For a 2-lane case, we investigated the case where each lane has equal effect (since this is an upper bound situation):

Stage 1 was to apply the spectrum to the lane 1 influence line and assess the damage. We see from our study of Model 2 (above) that we should magnify the stresses on longer influence lines by some parameter "Y". This is strongly dependent on influence line shape and length. We saw in column (2) of Table 2, above (the 2-span beam case), that its maximum value was 1.60 on damage. If we had run all vehicles in the spectrum in pairs, spaced at the two maximum points of the influence line, this could have given us 8 times the damage, which is much more than we need. However, suppose we ran some 10% of them in pairs. Then the damage (relative to the effect of a single vehicle) would have been $0.90 + (1 - 0.90) * 2^3 = 1.70$. Therefore we could run 10% of the spectrum in convoy pairs, and we suggest a centre to centre vehicle spacing of 40m could be adopted.

Stage 2 was to apply suitable numbers of spectrum vehicles in lane 2. Again, we could apply some 10% in convoy pairs.

Note that running vehicles in pairs will have little effect on simple influence lines (such as that represented in Table 1), or on short loaded lengths (i.e. under 50 m).

If we add the damage from lane 1 to that from lane 2, Table 2 tells us that (at 200m) we still have a shortfall in damage of 1/1.47, because we have not yet considered side-by-side running. However, this factor is very span-sensitive, and cannot be obtained merely by running some pre-determined proportion of vehicles side by side. Therefore, the complexities of modelling the effects of several vehicles at a time by running complicated combinations of possible groups appears to be an ineffective way of modelling side by side effects of a realistic traffic spectrum. It is suggested that the "Z" parameter as defined in

Figure 18 and specified in Figure 11 of BS5400: Part 10:1980 be adopted. This provides a length-dependent factor on damage of up to 1.50 for spans over 25 m (and from 1.0 to 1.5 in proportion to the logarithm of span from 3 m to 25 m).

3.1.3.5 Use of Model 5:

If a site-specific "Model 5" is developed, its application will be subject to the same rules as those described under "Use of Model 4", above.

3.2   Task 2: "Modifications to models 1, 2 and 3"

The relationship between the stress ranges caused by the fatigue models, and the fatigue effects caused by a flowing sequence of realistic UK heavy motorway traffic can be established.

Models 1 and 2 are to confirm unlimited life. The optimum geometry and magnitude of each of these models can only be established after extensive investigation of possible conversion charts such as those in BS5400: Part 10: 1980: Figure 8, modelling different traffic flows and influence line shapes. We decided to create damage assessment charts to compare the fatigue damage caused by the models with that caused by our best model of a realistic traffic spectrum. The charts were developed or single lane traffic effects, since the effects of several vehicles have been considered separately.

The user of the damage assessment chart takes the percentage of the stress range caused by the model, relative to the "constant amplitude - unlimited life", fatigue stress range. A different line is provided for each loaded length, and from that line the fatigue life can be obtained. The lines are based on lorry flows of 1 million per year, so the lives must be factored accordingly if flows are significantly different.

The charts account for the fatigue damage S-N curves given in prEN 1993-1-9 Figure 7.1.

3.2.1   Model 1 (similar to static LM1):

Model 1 is geometrically the same as static load model 1, so the same analysis processes are involved. When the load effect from this model causes a stress range equal to the constant amplitude non-propagating value, Figure 1 shows how model 1 provides life expectancies of some thousands of years.

Fatigue life for 1 million lorries per year for 100 years for 4 loaded lengths

Figure 1: Life expectancies of designs checked against Fatigue Model 1

We conclude that use of Model 1 is very conservative. This confirms that bridge details so designed would have effectively unlimited fatigue life, but it also implies that the model is much more onerous than it needs to be at all of these spans.

3.2.2   Model 2 (set of "frequent" vehicles):

Figure 2 presents predicted fatigue lives for details with stress cycle ranges of varying percentages of the effect of the largest range caused by the transit of the vehicles in Fatigue Model 2.

Life expectancies are only a little shorter than for designs checked to Model 1. The Model 2 check provides slightly better consistency over a range of spans than does the Model 1 check.
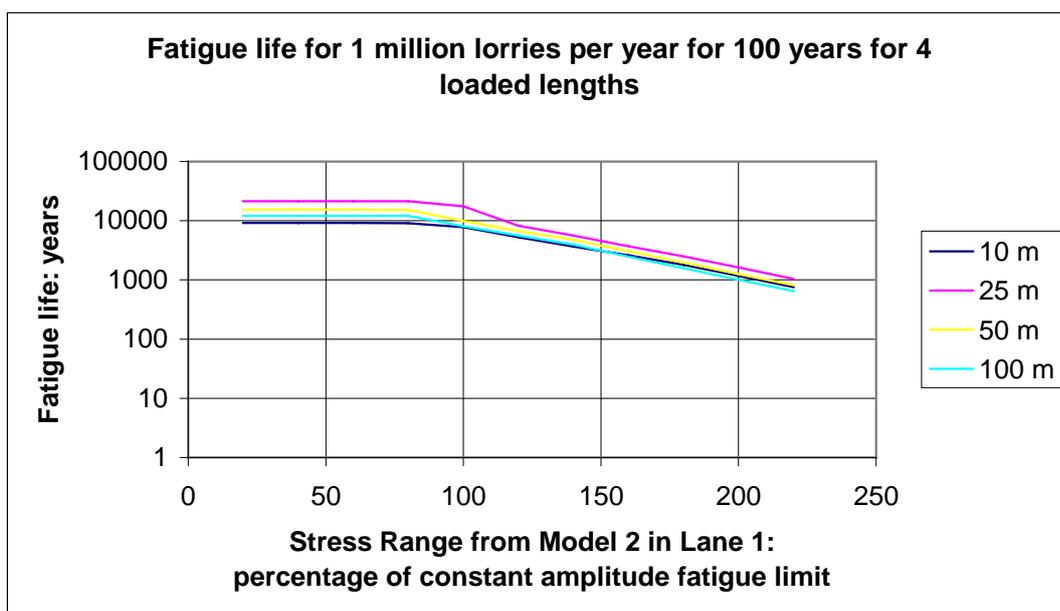
Fatigue life for 1 million lorries per year for 100 years for 4 loaded lengths

Figure 2: Life expectancies of designs checked against Fatigue Model 2

Model 2 comprises 5 vehicles of which, on a simple beam influence line, only the second and third vehicles produced peak stress ranges. In principle, Model 2 appears to be an improvement on Model 1, and is less conservative. We do not consider that modifications to Model 2 are necessary.

3.2.3   Model 3:

According to **4.6.1(2) b),** Model 3 is to be used to calculate maximum stress ranges.

Clause **4.6.1(2) d)** states that Fatigue Load Models 3, 4 and 5 "should not be used to check whether fatigue life can be considered as unlimited". Clause **4.6.1(2) d)** states that Fatigue Load Model 3 may be used in direct verification of designs by taking account of traffic volume and bridge dimensions by a material-dependent factor λ_e, and the note under **4.6.4** states that the "conditions of application of this rule" may be defined in the National Annex.

BS EN 1991-2:2003 provides no basis for developing λ_e. BS5400 provides a method of application for a very similar fatigue load model by means of the damage assessment chart in Figure 10. The rules accompanying this chart allow "direct verification of designs".

Figure 3 presents a similar damage assessment chart to those for Models 1 and 2. We concluded that the damage assessment chart for this model for bending effects had good consistency over a range of spans and weld details. It provide to be less conservative than either using Model 1 or Model 2, although (notwithstanding what the code states) it still appears to provide effectively about 500 years life expectancy (which is practically unlimited) for items designed to the constant amplitude non-propagating stress under Model 3. In our view, the model does not require any modification. However, if it to be used to provide life predictions, it should be used in association with additional information (such as Figure 3) in order to cater for multiple vehicles on a span, multiple lanes, and different influence line shapes.
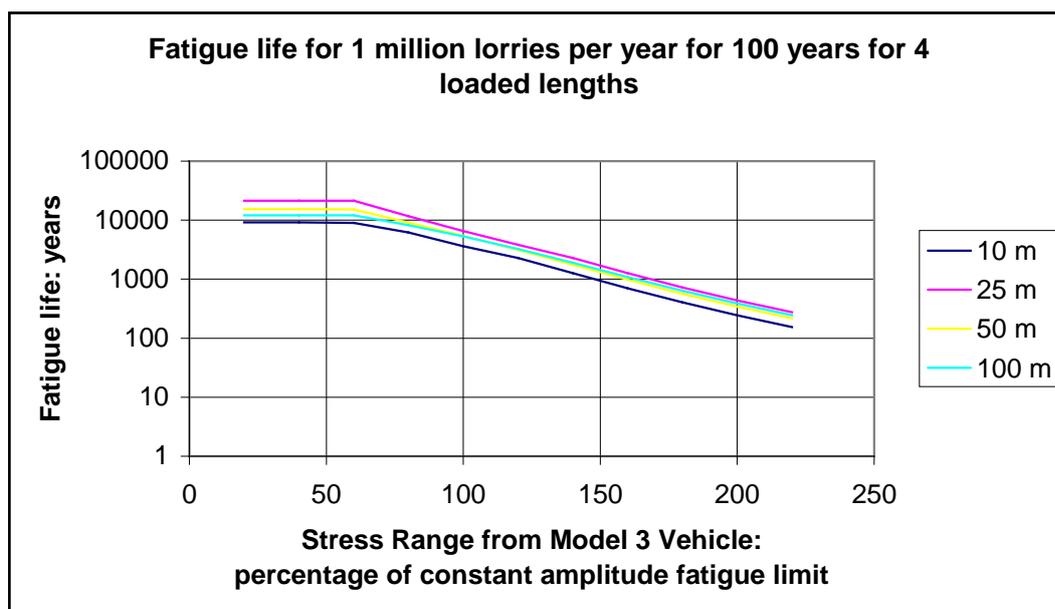

Figure 3: Life expectancies of designs checked against Fatigue Model 3

3.3   Task 3: "Consider … traffic categories"

The traffic flow categories that appear in BS5400: Part 10 were intended to represent peak capacities for different types of road. They were intended for use in design because it was considered that since the choice of type of new road construction depended on the predicted traffic flow, so the table provides self-fulfilling prophesies.

Table 3 compares the BS5400 and BS EN 1991-2:2003 recommendations for design flow rates for commercial vehicle traffic on different roads. It includes approximate observed values from two heavily trafficked UK motorway sites.

Road Type	BS 5400: Part 10		BS EN 1991-2	
	Lane 1	Lane 2	Lane 1	Lane 2
Warrington, year 1990 3 lane motorway record	2.8	1.8	2.0	1.0
M6 Coventry, year 2000 3 lane motorway record	3.0			
Roads and motorways with high lorry flow rates			2.0	0.2
Roads and motorways with medium lorry flow rates			0.5	0.1
Main roads with low lorry flow rates			0.125	0.0125
Local roads with low lorry flow rates			0.050	0.005
Motorway: 3 lanes	2.0	1.5		
Motorway: 2 lanes	1.5	1.0		
Dual all purpose road: 3 lanes	1.5	1.0		
Dual all purpose road: 2 lanes	1.5	1.0		
Slip road: 2 lanes	1.5	1.0		
Single all purpose road: 3 lanes	1.0	n/a		
Single all purpose road: 2 lanes	1.0	n/a		
Slip road: 1 lane	1.0	n/a		
Single all purpose road: 2 narrow lanes	0.5	n/a		

Table 3: Numbers of millions of commercial vehicles per year

We projected from a single weekday sample of 1990 Warrington M6 data that there were close to 3 million goods vehicles using Lane 1, with 1.8 million using Lane 2, whereas BS5400: Part 10 indicates 2.0 and 1.5 million respectively. BS EN 1991-2 recommends 2.0 and 0.2 million respectively.

The year 2000 DTLR traffic census statistics show considerable variation in goods vehicle flows at different sites. The Lane 1 record for M6 near Coventry shows 1,570,000 vehicles with 3 or more axles, which gives a number of about 3,000,000 for all commercial vehicles. This is similar to the Warrington 1990 figure. However, this site is the busiest in our records, and recent new road building has taken place in order to reduce congestion at this point. That tends to suggest that the BS5400 figures are reasonably close to the upper bound that is socially and politically acceptable at present, so they would seem to provide a reasonable basis for design.

BS EN 1991-2:2003 provides for different proportions of the various types of heavy goods vehicle according to whether traffic is "long distance", "medium distance" or "local traffic". This distinction is not made in BS 5400. We suggest that such distinctions are not very relevant in the relatively densely populated UK, and that the values for "medium distance"

traffic be used in all cases. This has the advantage that 50% of the "set of equivalent lorries" in fatigue model 4 comprises multi-axle lorries, which matches the BS5400 spectrum, and therefore ensures that the comparisons between flows on different types of road (see Table 4, above) are valid.

We recommend that the BS 5400: Part 10: 1990 figures in Table 1 be retained for UK highway design. The BS EN 1991-2:2003 values may be applied to local roads.

3.4   Task 4: "Define amplification factors near expansion joints"

The Eurocode traffic models provide for stress enhancement for traffic loading on zones of bridges close to expansion joints. These values were based on extensive research during the development of the traffic load models. The amplification factor provided in Figure 4.7 of BS EN 1991-2:2003 varies linearly between 1.30 at the joint to 1.00 at 6.0 m from the joint. Figure 7 of BS5400: Part 10: 1980 is very similar, varying from 1.20 at the joint to 1.00 at 5.0 m from the joint. We recommend that, in the interests of harmonisation, the BS EN Figure 4.7 values be adopted in the National Annex.

3.5   Task 5: "Define adjustments to Model 3 for different road types"

All motorway traffic starts its journeys on non-motorway roads, and the data that we have reviewed from various sites in the past indicates that the weights of vehicles of each particular type depend much more on the type of vehicle than on the place or type of road. Model 3 is to be used to establish stress ranges, and we consider that (provided that the damage assessment method that uses this information is correctly calibrated), the model need not be adjusted to cater for different road types.

3.6   Task 6: "Define Circumstances for using Model 4"

Model 4 is intended to provide the most accurate basis for projecting fatigue lives, in the absence of traffic data obtained at the actual bridge site. The "unlimited life criteria" provided by Models 1 and 2 are very conservative in most circumstances, and Model 4 ought to provide more economical solutions. However, the degree of saving in materials will be offset to some extent by the additional calculation effort, so Model 4 is likely to be most appropriate on large projects where weight saving is particularly important (e.g. suspension and cable stayed bridges) or where the design effort will be offset by economy of scale where mass production and replication of common details take place.

The actual integrated damage produced by Model 4 as it appears in Table 7 of BS EN 1991-2:2003 (calculated assuming a constant power law of 3.0 on stress range) is very much more than that obtained using the BS5400: 1980 spectrum. There are several reasons for this:

* Model 4 was derived from French heavy goods vehicle data. The records indicated that these were typically significantly heavier than similar UK vehicles.
* The total weight of 1 million Model 4 vehicles in the "medium distance" journey model is 3300 MN, whereas that in the UK spectrum presented in the draft BD9 is only 1500 MN. Fatigue damage is (typically) approximately proportional to the third power of stress, so this markedly increases the amount of damage from Model 4.

Note 2 under **4.6.5 (1)** of BS EN 1991-2:2003 states "Other standard lorries and lorry percentages may be defined for the particular project or in the National Annex". Accordingly we recommend that the table provide in the FNP draft Appendix BD9 document be used in place of Table 4.7.

The relative merits of using Models 3 and 4 will depend on the complexity of the adjustment factors that are provided to cater for different spans and influence line shapes when using Model 3. The damage assessment chart shown in Figure 1, above, was developed for simple moment influence lines. If lines are more complex, Model 4 might provide a more appropriate basis for calculation, since it allows more realistic damage assessment.

Model 4 should also be used wherever influence line lengths are short and have reversals in sign within loaded lengths that are similar to typical vehicle dimensions, for which the stress cycle pattern is sensitive to individual vehicle wheelbases.

Note e) under **4.6.1** states that Model 4 may be used "when the simultaneous presence of several lorries on the bridge can be neglected. If that is not the case, it should only be used if it is supplemented … in the National Annex".

Since it is possible to establish the difference between the effect of single lane traffic and multiple lane traffic by means of load effect simulation analysis using data acquired on busy roads, it should be possible to formulate suitable rules to assess simultaneous lane load effects, relative to the effects of traffic running independently in each of several lanes. We suggest such rules under "Task 1", above.

3.7   Task 7: "Specify circumstances for using Model 5"

Model 5 requires the designer to derive a traffic model based on actual observation of traffic at the site. This will seldom be justifiable except for places where knowledge of local traffic conditions is poor (e.g. especially at foreign locations where existing UK traffic data provides a poor model for local traffic), or where existing structures are found to be unsatisfactory when they are under review.

4   DRAFT PROVISIONS FOR NATIONAL ANNEX

4.1   Introduction

The following table lists the clauses in BS EN 1991-2:2003 that are permitted to be altered or supplemented in the National Annex. The first column is copied from the Highways Agency project brief. The second column is copied from Page 12 of BS EN 1991-2:2003, which describes where National Choice is permitted. The third column is derived from the text of the document.

Highways Agency Brief	BS EN 1991-2:2003 list	BS EN 1991-2:2003 text	Subject
4.6.1(2) Note 2(c)	*4.6.1(2) Note 2*		*Conditions of use of models 1 and 2*
4.6.1(2) Note 2(e)	*4.6.1(2) Note 2*		*Additional data for use with model 4*
4.6.1(2) Note 4		*4.6.1(2) Note 4*	*Modification to values of models 1 and 2*
4.6.1(3) Note 1	*4.6.1(3) Note 1*	*4.6.1(3) Note 1*	*Traffic categories and flows*
4.6.1(6)	*4.6.1(6)*	*4.6.1(6)*	*Dynamic amplification*
4.6.2(1)			*Fatigue load model 1*
4.6.4(3)	*4.6.4(3)*	*4.6.4(3)*	*Conditions for use of model 3 for more than one vehicle per lane*
4.6.5(1) Note 2	*4.6.5(1) Note 2*	*4.6.5(1) Note 2*	*Other standard lorry definitions*
4.6.6(1)	*4.6.6(1)*	*4.6.6(1)*	*Use of model 5 (recorded data)*

There appears to be a significant conflict with regard to clause 4.6.1(2) Note 4, in which the summary table makes no reference to modifications to Fatigue Models 1 and 2, whereas the text does. Furthermore, the text makes no reference to several of the changes that are allowed in the summary table. We are providing proposals for text changes wherever either the table or the text permits.

DRAFT NATIONAL ANNEX PROVISIONS:

4.6.1(2) Note 2(c)
Fatigue Load Model 1 requires no modifications to consider simultaneous presence of several lorries on a bridge.

Where bridge influence line lengths permit, the maximum and minimum stresses caused by Fatigue Load Model 2 shall be obtained by considering the worst load effect of the most onerous vehicle accompanied at a 40 m centre to centre distance by the lightest vehicle in Table 4.6, if this causes a worse load effect. Where two or more traffic lanes influence the design detail, the maximum and minimum stresses shall be obtained from Fatigue Model 2 by placing the most onerous vehicle on the most onerous part of the influence line in the most onerous lane, plus the lightest vehicle on the most onerous part of the influence line in one adjacent lane.

4.6.1(2) Note 2(e)
Where bridge influence lengths permit or where two or more traffic lanes influence the design detail, Model 4 shall be applied as follows:

The fatigue damaging stress cycles due to transit of Model 4 shall be assessed and counted using the rainflow counting procedure described in prEN 1993-1-9. Unless required by special project circumstances, fatigue damage shall be assessed on the basis of stress cycles calculated from two traffic lanes only. These lanes (described as Lanes 1 and 2) are the two traffic lanes that individually cause the most theoretical fatigue damage in the component under consideration. Vehicle numbers in these lanes shall be obtained from Table 4.5.

Damage summation D_d shall be obtained by adding contributions from the following cases:

- Lane 1 traffic alone, with 80% of Lane 1 lorry numbers:
- 20% of Lane 1 traffic running in convoy with vehicles at 40m centre to centre spacing
- Lane 2 traffic alone, with 80% of Lane 2 lorry numbers
- 20% of Lane 2 traffic running in convoy with vehicles at 40m centre to centre spacing

The effect of side-by-side running shall be allowed for by multiplying the total damage D_d by a factor Kb.Z, where:

  Kb = ratio of the maximum stress range caused by single vehicles in lane 2 to the maximum stress range caused by single vehicles in lane 1
and
  If loaded length < 3.0 m, Z = 1.0
  If 3.0 < loaded length < 20 m, Z varies linearly in proportion to the logarithm of the loaded length from 1.0 to 1.5
  If 20 < length, Z=1.5

4.6.1(2) Note 2(f)
If a site-specific "Model 5" is developed, its application will be subject to the same rules as those described under **4.6.1(2) Note 2(e)**, *above*.

4.6.1(2) Note 4
No alterations are recommended to Fatigue Load Models 1 and 2 to cater for different categories of traffic.

4.6.1(3) Note 1
Heavy vehicle numbers for use in fatigue design in the United Kingdom shall be assumed to be as indicated in Table 4.5. Heavy vehicle counts may be obtained from site surveys by doubling the numbers of lorries observed to have three or more axles.

NOTE 5: Basing the numbers of heavy vehicles on counts of multi-axled lorries ensures a reasonably reliable match between the numbers of the vehicle types that cause most potential fatigue damage in the actual traffic and the codified traffic model.

NOTE 6: The values presented in Table 4.5 are design values that are intended to reflect approximate road capacities, and they may not match observations of current usage. Traffic flows at a small number of sites may exceed these values, but the differences are unlikely to have a very significant influence on designs.

Traffic Categories			N_{obs} per lane (millions per year)	
Type	Carriageway layout	Number of lanes per carriageway	Each slow lane	Each fast lane
Motorway	Dual	3	2.0	1.5
Motorway	Dual	2	1.5	1
All purpose	Dual	3		
All purpose	Dual	2		
Slip road	Single	2		n/a
All purpose	Single	3	1.0	0
All purpose	Single	2		0
Slip road	Single	1		n/a
All purpose	Single	2	0.5	0
Local (low lorry flow)	Single	2	0.05	0

Table 4.5 – Indicative numbers of heavy vehicles expected per year and per lane in the United Kingdom

4.6.1(6)
We recommend that the BS EN 1991-2:2002 Figure 4.7 values be adopted.

4.6.2(1)
NOTE 1: Fatigue Load Model 1 is very conservative and, in most cases, a detail exposed to a lorry flow rate of 1,000,000 per year and designed such that its stress range does not exceed the theoretical non-propagating value under the standard Fatigue Model 1 loading will have a predicted life substantially greater than required.

4.6.4(3)

Fatigue Load Model 3 is used to determine the fatigue life of the detail in question from calculated stress ranges, and may be used where Fatigue Models 1 and 2 fail to demonstrate unlimited life.

It is applicable in the following cases:

- The fatigue strength curves are as presented in Figure 7.1 of prEN 1993-1-9
- The traffic load model may be reasonably described by the spectrum presented in Fatigue Load Model 4.

The method of application and interpretation is as follows:

- Apply the fatigue model to each traffic lane in turn
- Calculate stress ranges in design details
- Take overall stress range equal to larger of:
  o   Maximum stress stress range from worst loaded lane plus 20% of maximum stress range in second worst lane
  o   Difference between extreme stress range from worst lane loaded and opposite extreme from any adjacent lane
- Amplify stress range in accordance with Figure 4.7 if applicable
- Calculate the percentage of the stress range to the constant amplitude fatigue stress range for the detail in question
- Look up this percentage on the assessment chart in Figure 4.8.1 to obtain fatigue life in years
- Factor the fatigue life by the ratio of 1 million to the annual lorry flow in the worst lane.
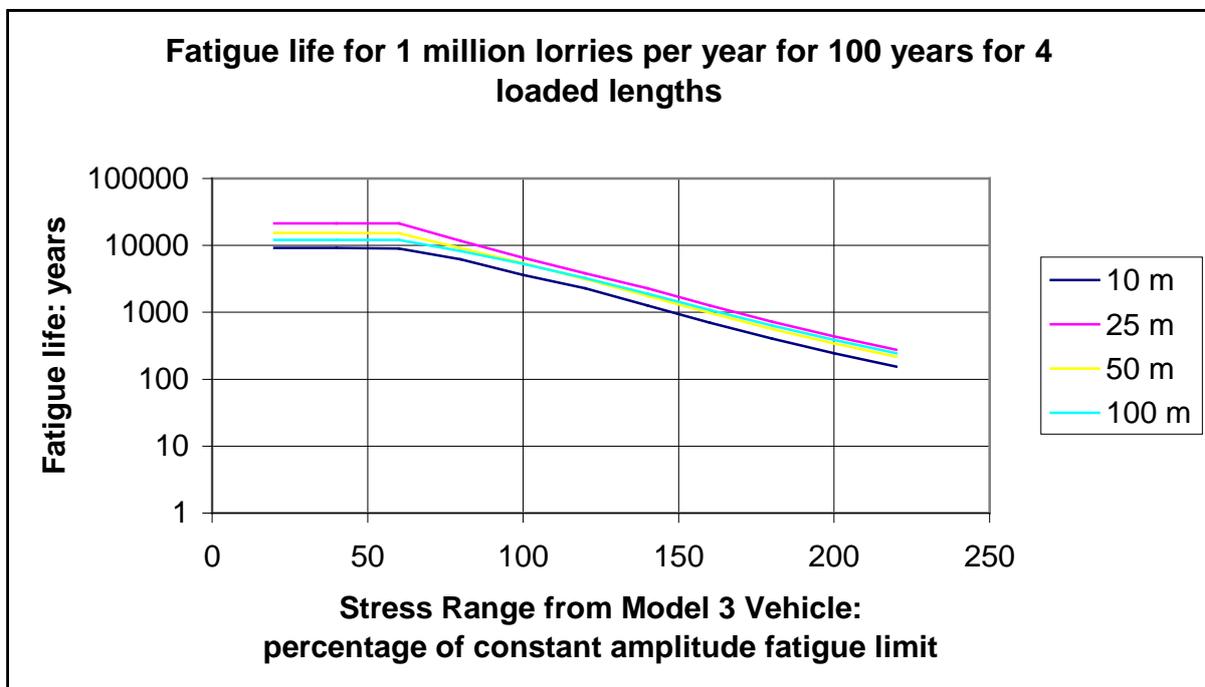

Figure 4.8.1: Damage Assessment Chart for Fatigue Model 3

4.6.5(1) Note 2

Fatigue load model 4 may be used where models 1, 2 and 3 all fail to provide assurance of sufficient fatigue life. Model 4 should also be used when influence line lengths are

short enough to have reversals in sign within loaded lengths that are similar to typical vehicle dimensions, for which the stress cycle pattern is sensitive to individual vehicle wheelbases.

Table 4.7 defines the properties of standard lorries for use in fatigue design in the United Kingdom.

NOTE 1: The characterisation of road traffic for fatigue design purposes depends on the traffic lane configuration, traffic flow rates, proportions of goods vehicles, types of goods vehicles and vehicle usage.   Traffic flow rates are very route-dependent. However, road provision is made approximately in relation to demand, and it is recommend that the highway traffic flow rates that are presented in Table 4.5 be adopted for design in the United Kingdom. Table 4.7 requires no modification for road type.

NOTE 2: Table 11 of BS5400: Part 10: 1980 provides an acceptable alternative model, the use of which will typically introduce differences of under 25% on fatigue life predictions.

4.6.6(1)
The derivation of a site-specific model of the traffic spectrum is only likely to be justifiable in unusual circumstances, for example:
- Where knowledge of local traffic conditions is poor (e.g. at foreign locations where existing UK or European traffic data provides a poor model for local traffic).
- Where local circumstances are very particular (e.g. at factory approaches or sea ports).

Some guidelines to model development include:
- Limited data indicate that the nature of use and therefore the weight distributions of each type of heavy goods vehicle appear to be depend more on the country (and thus the legislative and control frameworks) than to sites within individual countries
- Certain sites are particularly subject to asymmetric flows, and vehicle populations may contain unusually large fractions either of fully laden or of empty vehicles. Such sites might include access routes to mines or quarries, to large industrial locations and to port facilities.
- It is most important to accurately model the numbers of the heavier vehicle types. Estimates of "total goods vehicle flow" may therefore be very misleading, owing to the very variable means of monitoring and classifying twin axle lorries. We recommend that care be taken to correctly estimate numbers of lorries with three or more axles, and to correctly match the numbers of such vehicles to those in general traffic models where these are used.

Total axles	Chassis type	Average axle spacings, m	Loading group	Total weight kN	Axle loads, kN	No. in each group per million commercial vehicles	Vehicle Designation
18	Girder Trailer and 2 tractors	4.5 1.5 4.0 1.5(5no.) 13.5 1.5(5no.) 4.0 4.5 1.5	H	3680	80 160 160 240(6no.) 240(6no.) 80 160 160	10	18GT-H
			M	1520	80 160 160 60(6no.) 60(6no.) 80 160 160	30	18GT-M
9	Tray Trailer and tractor	4.5 1.5 4.0 1.5 1.5 1.5 1.5 1.5	H	1610	70 140 140 210 210 210 210 210 210	20	9TT-H
			M	750	50 110 110 80 80 80 80 80 80	40	9TT-M
7	Girder Trailer and tractor	4.5 1.5 4.0 2.0 10.0 2.0	H	1310	70 140 140 240 240 240 240	30	7GT-H
			M	680	60 130 130 90 90 90 90	70	7GT-M
	Articulated	3.0 1.5 9.5 1.5 1.5 1.5	H	790	70 100 100 130 130 130 13 0	20	7A-H
5	Articulated	3 1.5 9.5 1.5	H2	630	70 130 130 150 150	280	5A-H2
		3.5 5.5 1.5 1.5	H	380	70 100 70 70 70	90500	5A-H
			M	300	50 70 60 60 60	90000	5A-M
			L	190	40 60 30 30 30	90000	5A-L
4	Articulated	3.0 6.5 1.5	H	240	40 80 60 60	45000	4A-H
			M	175	40 55 40 40	45000	4A-M
			L	145	35 50 30 30	45000	4A-L
	Rigid	1.5 3.5 1.5	H	280	50 50 90 90	8000	4R-H
			M	240	40 40 80 80	8000	4R-M
			L	120	20 20 40 40	8000	4R-L
3	Articulated					Not Used	3A
	Rigid	4.0 1.5	H	240	60 90 90	10000	3R-H
			M	195	45 75 75	10000	3R-M
			L	120	60 45 45	10000	3R-L
2	Rigid	4.0	H	135	50 85	170000	2R-H
			M	65	30 35	170000	2R-M
			L	30	15 15	200000	2R-L

Key: ● Standard axle. 4 tyre, 1.8m track ◎ Steering axle. 2 tyre, 2.0m track ⬤ Special axle. 2 to 8 tyres, up to 3.4m outer track. All vehicles over 5 axles

Table 4.7: Set of equivalent lorries

5   INCONSISTENCIES IDENTIFIED IN BS EN 1991-2:2003

During the preparation of proposals for the clauses on Fatigue Load Models in the National Annex to BS EN 1991-1:2003, several inconsistencies were identified. These are listed below.

- There appears to be a conflict between paragraph 4.6.4(2) and 4.6.1(2) Note 2d. The former states that stress ranges must be calculated for Fatigue Load Model 3, but makes no mention of stress cycle counts or of Miner's rule summation. The latter, however, clearly states that Model 3 is to be used for fatigue life assessment. It provides no guidance on how this is to be done, apart from the use of an undefined parameter λ_e. In the UK, Figure 10 of BS5400: part 10: 1980 provides such guidance, but none is given in BS EN 1991-2:2003.

- 4.6.1(2) f) Note 4 states that Fatigue Load Models 1 and 2 may be modified "when considering other categories of traffic". The term "other" is not defined except in the previous note. It appears to be inconsistent that "α" values may be defined in the National Annex to modify the static design load model LM1, but these same "α" values do not re-appear in **4.6.2**. This leads to an over-conservative Fatigue Load Model 1.

- The symbol λ_e noted above does not appear in the list of symbols used in Section 4, which appears in 1.5.2 on page 22, nor is its location (if any) in other Eurocodes described.

- As we note in Section 4 of this report (above), the list of clauses that are permitted to be altered by the National Annex is incomplete. 4.6.1(2) Note 4 says that Fatigue Load Models 1 and 2 may be altered, but 4.6.2 does not mention this, and neither does the summary table allow changes to 4.6.2 in which these models are defined.