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Management Strategies for Special Permit Vehicles for Bridge Loading

Bernard Enright
Technological University Dublin, bernard.enright@tudublin.ie

Eugene J. OBrien
University College Dublin

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Bernard Enright
Lecturer
Dublin Institute of Technology
Dublin, Ireland
bernard.enright@dit.ie

Eugene OBrien
Professor
University College Dublin
Dublin, Ireland
eugene.obrien@ucd.ie

Abstract

An examination of weigh-in-motion (WIM) data collected recently at sites in five European countries has shown that vehicles with weights well in excess of the normal legal limits are found on a daily basis. These vehicles would be expected to have special permits issued by the responsible authorities. It can be seen from the WIM measurements that most of them are travelling at normal highway speeds (around 80 km/h). Photographic evidence indicates that, while many are accompanied by an escort vehicle in front and/or behind, normal traffic is flowing alongside in other lanes of the highway. As European freight volume grows, the frequency of these special vehicles can be expected to increase. Hence, the probability of them meeting a heavy truck travelling in the opposite direction on a bridge also increases.

Gross vehicle weights in excess of 100 t have been observed at all sites, and are a daily occurrence in the Netherlands. Most of these extremely heavy vehicles are either mobile cranes or low loaders carrying construction equipment. Both types have multiple axles at very close spacing, and the gross weight and axle layout have implications for bridge loading.

This paper presents findings based on a simulation model which incorporates the load effects for all observed truck types on short to medium span bridges. It is evident that special vehicles govern the lifetime maximum bridge loading, and the occurrence of extremely heavy trucks is sufficiently frequent that meeting events can be expected during the design lives of the bridges. The effects of different management strategies for special permit vehicles are modelled and the results are presented.

1. Introduction

While the debate continues on raising legal limits on truck dimensions to 25.5 m and weights to 60 t, measurements show that much heavier vehicles are already encountered on European highways on a regular basis. These vehicles would be expected to have special permits issued by road authorities in each member state, but it is clear that they occur frequently and impose severe loading on road bridges. As the frequency increases, the probability of them being on a bridge simultaneously with other heavy trucks also increases. The resulting bridge loading is likely to increase the already high cost of maintaining existing bridges and infrastructure. The importance of special permit vehicles in bridge loading has also been recognized by authors in the United States (Moses, 2001; Sivakumar et al., 2007)

In recent years, the improved quality and increasing use of weigh-in-motion (WIM) technology (Jacob and O'Brien, 2005) has meant that more accurate measurements of vehicle weights are

now available for periods covering many months or even years of traffic at selected locations. These extensive measurements can be used to refine probabilistic bridge loading models for the assessment of existing bridges, and to monitor the implications for bridge design of trends in vehicle weights and types. The application of site-specific models for bridge assessment has been widely studied (Moses, 2001; Sivakumar and Ibrahim, 2007). A common approach is to measure traffic data for some weeks, to fit a statistical distribution to the calculated load effects for the measured traffic, and to use these distributions to estimate maximum lifetime effects (Miao and Chan, 2002; Nowak, 1993). This estimation may require a considerable degree of subjective judgement (Kulicki et al., 2007). An alternative approach adopted by many authors is to use Monte Carlo (MC) simulation (Bailey and Bez, 1999; O'Connor and O'Brien, 2005). For this, statistical distributions for vehicle weights, inter-vehicle gaps and other characteristics are derived from the measured traffic, and are used as the basis for the simulation of traffic for a number of years. In this study, MC simulation models based on extensive collections of weigh-in-motion (WIM) data are used to examine the effects of different possible management strategies for these special permit vehicles. The strategies examined focus on managing the frequency, type and weight of these vehicles with the aim of keeping bridge loading within acceptable levels. Short to medium span bridges are considered where free flowing traffic with dynamics is taken to govern lifetime maximum loading (Bruls et al., 1996)

2. Measured truck data

Traffic measurements were collected for nearly three million trucks at five European motorway sites using weigh-in-motion technology, as shown in Table 1. WIM measurements include the gross vehicle weight (GVW), speed and wheelbase for each truck, individual axle weights and spacings, and inter-vehicle gaps. At the site in Slovakia, traffic was recorded in the slow lane in each direction. At the other four sites, the measurements are for the slow and fast lane in one direction, with more than 92% of trucks recorded in the slow lane. A notable feature at all sites is the very high maximum GVWs recorded.

Table 1   Summary of WIM data

Country	Netherlands	Slovakia	Czech Republic	Slovenia	Poland
Site	Woerden	Branisko	Sedlice	Vransko	Wroclaw
Road number	E25	E50	E49	E57	E40
Directions	1	2	1	1	1
Total trucks	646 548	748 338	729 929	147 752	429 680
Time span	Feb-Jun 2005	Jun'05-Dec'06	May'07-May'08	Sep-Nov 2006	Jan-Jun 2008
ADTT[a]	7 102	1 100	4 751	3 293	4 022
Maximum GVW (t)	165.6	117.1	129.0	131.3	105.9
Number over 60 t	1 716	556	376	15	587
Number over 75 t	744	48	90	3	18

Note: [a] ADTT is average daily truck traffic in one direction on weekdays

The GVW histograms for all sites are illustrated in Figure 1. The distribution of weights up to 70 t shown in Figure 1 (a) and (c) is typical of heavily trafficked European highways (O'Connor and O'Brien, 2005; Bailey and Bez, 1999). Significant numbers of very heavy vehicles were also recorded at all sites, as can be seen in Figure 1 (b) and (d).
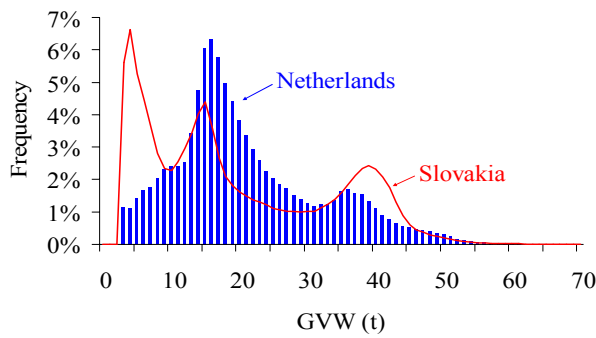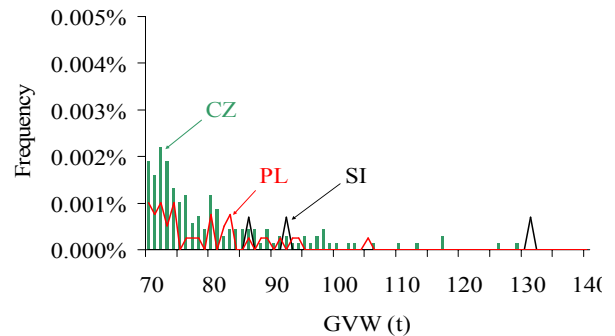
(a) Netherlands and Slovakia – Less than 70 t
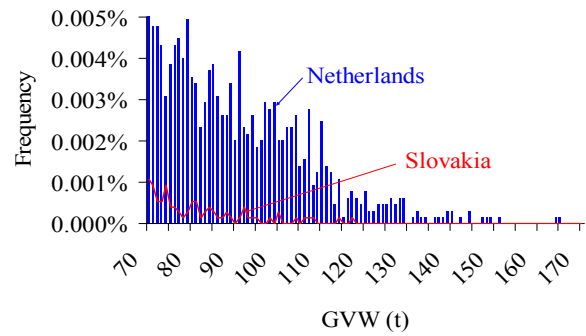
(b) Netherlands and Slovakia – Over 70 t
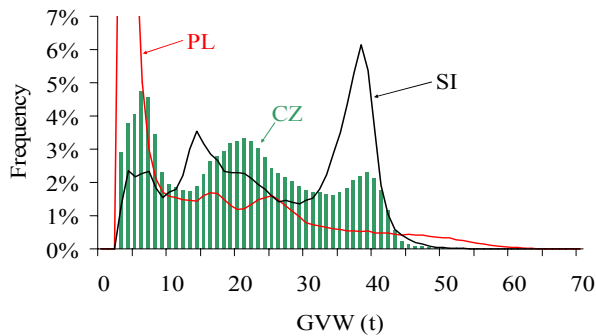
*(c) Poland (PL), Czech Republic (CZ) and
Slovenia (SI) – Less than 70 t*

*(d) Poland, Czech Republic and Slovenia -
Over 70 t*

Figure 1   Gross vehicle weight distributions

Photographic evidence from the WIM site in the Netherlands was used to help in the classification of extremely heavy vehicles. As GVWs increase above 50 t, two types of vehicle become predominant. Crane-type vehicles which are characterised by having all axles closely-spaced (as in Figure 2(a)) are found up to 120 t. Low loaders tend to have two groups of closely-spaced axles with the groups separated by a relatively large gap of around 10 m (as in Figure 2(b)). They become increasingly evident from 50 t upwards, and are the single dominant type above 120 t.

(a) 8-axle crane, 101 t

(b) 11-axle low loader, 145 t

Figure 2   Extreme vehicle types

These extreme vehicles are recorded in the WIM data travelling at typical highway speeds of 80 km/h and are usually followed in the same lane by an escort vehicle, but are often adjacent to normal traffic in other lanes. Sites other than the Netherlands have relatively few trucks in excess of 100 t, but similar trends are evident and, for vehicles above 100 t, the Netherlands is used here as the template for extreme vehicle types.

3. Simulation of bridge loading

The Eurocode for the design of bridges (EC1, 2003) specifies that the values of lifetime maximum (characteristic) load effects (bending moment, shear force) should be those values with a 5% probability of occurrence in a 50-year period, and this is equivalent to the values that occur on average once every 1000 years. For a particular site, these characteristic load effects can be estimated by using Monte Carlo simulation of traffic using a set of statistical distributions based on observed data for each of the random variables being modelled. The simulation can be run for a number of years of traffic, and lifetime maxima can be extrapolated from the results. The approach used here is to greatly reduce the uncertainty associated with extrapolation by developing an optimized model that makes it practical to simulate a thousand years of traffic. This approach also makes it possible to examine the loading scenarios that produce the maximum lifetime loading.

The characteristics of the simulated traffic are based on those of traffic which was measured over a period of months. For gross vehicle weight and vehicle class (as defined here by the number of axles on the vehicle), a semi-parametric approach is used as described by O'Brien et al. (2009). This uses a bivariate empirical frequency distribution in the regions where there are sufficient data points. Above a certain GVW threshold value, the tail of a bivariate Normal distribution is fitted to the observed frequencies, and this allows vehicles to be simulated that may be heavier than, and have more axles than, any measured vehicle.

Bridge load effects for the spans considered here are very sensitive to wheelbase and axle layout. Within each vehicle class, empirical distributions are used for the maximum axle spacing for each GVW range. Axle spacings other than the maximum are less critical and trimodal Normal distributions are used to select representative values. The proportion of the GVW carried by each individual axle is simulated using correlated bimodal Normal distributions fitted to the observed data for each axle in each vehicle class.

Bidirectional traffic on a two-lane bridge is analysed here. For the purposes of this study, two sites are modelled – Slovakia (SK) and the Czech Republic (CZ). Average traffic volumes in one direction at these sites are 1100 trucks per day in Slovakia, and 4750 in the Czech Republic. The WIM data for the Czech site is taken from a dual carriageway road and it is acknowledged that it is conservative to assume it to be present on a bridge with bi-directional traffic. The traffic volumes in the Netherlands (7100 trucks per day) are very high, and most unlikely to be carried on a bridge of this type. The simulation is run for four bridge lengths – 15, 25, 35 and 45 m. Annual maximum values are calculated for three load effects – mid span bending moment on a simply supported bridge (LE1), support shear at the entrance to a simply supported bridge (LE2) and hogging moment over the central support of a two span continuous bridge (LE3). These annual maxima can be used to calculate the lifetime maximum loading, and also to examine the type of loading scenarios that produce load effects at or near the lifetime maximum.

Lateral distribution of traffic loads depends on the type of bridge, and this is accounted for by applying different lane factors to truck weights in one lane. On bridges with low lateral distribution, the maximum stresses typically occur under one lane, and the relative contribution from trucks in the second lane is lower. The factors used here are based on finite element analyses carried out by the authors (Enright and O'Brien, 2009). For bending moments on bridges with high lateral distribution, the factor is 1.0 (i.e., no reduction), and 0.45 for low distribution. Maximum shear at the supports occurs when trucks are close to the support, and there is less opportunity for lateral distribution. In this case, a factor of 0.45 represents high distribution, and 0.05 is low.

4.   Lifetime maximum loading scenarios

Scenarios that produce load effects at or near the lifetime maximum value on bridges of two different lengths (15 and 35 m) are summarised in Table 2. These are for current traffic with no weight restrictions and in each case are based on the top twenty simulated annual maximum load effect values in 1000 years. Two types of loading event are important – a single extremely heavy truck on the bridge (shown in the table as a single GVW), and a meeting event where an extremely heavy truck meets a standard truck (shown in the table as, e.g., 120 || 40). Meeting events featuring two extremely heavy trucks are rare at both sites. They do happen – there are cases in the simulation of two 90 t trucks meeting, but the probability of them meeting, for example, at the centre of the bridge is low.

Table 2   Typical lifetime maximum loading scenarios showing GVW of truck(s)

Lateral Distribution	Site	Bridge length (m)	Load Effect		
			LE1	LE2	LE3
High	Czech Republic	15	115 || 36	125	115 || 36
		35	120		40	165	155		40
	Slovakia	15	85 || 45	105	90 || 40
		35	90		45	130	135		40
Low	Czech Republic	15	130	125	120
		35	145	165	160
	Slovakia	15	100	105	110
		35	120	135	150

It is clear that, for all spans considered, lifetime maxima are dominated by extremely heavy trucks, and these are most likely to be cranes and low loaders. Cranes have a relatively short wheelbase and this tends to concentrate the load and gives relatively high bending moments at mid span and shear at supports of simple supported spans. Low loaders also have groups of heavily loaded and closely-spaced axles which can produce high load effects in simply supported spans, and they also tend to produce relatively high hogging moments over intermediate supports in multi-span bridges when they straddle the support.

5.   Management strategies for extreme vehicles

This study examines the effects of different management strategies for extreme vehicles. These vehicles would all be expected to have special permits, and road authorities who might be considering altering their permit policies need to understand the effects of such policy changes on bridge loading. For example, as economic activity increases, it is to be expected that the number of permit applications will also increase. On the other hand, authorities may seek to reduce bridge loading by limiting the number of permits and hence the frequency of these vehicles. Another option is to limit the maximum weights permitted. In all cases, there is always the possibility of overweight illegal trucks, which may be more difficult to control.

5.1 Managing frequency

Strategies were simulated ranging from reducing the frequency of heavy vehicles to 25% of their current volumes (as measured in the WIM data) up to a doubling of the current frequencies. For this, a threshold value of 75 t was used, and the simulated frequencies above this threshold were scaled by the appropriate factor. Sample results are shown in Figure 3, and it can be seen that the two strategies change characteristic lifetime maximum load effects by approximately 5%. There is a certain amount of randomness in the estimation process, and changes of less than 3% cannot be assumed to be significant. Intermediate strategies such as increasing or decreasing frequencies by 50% do not have a significant impact on the lifetime loading. Increasing the frequency of extremely heavy trucks increases the maximum weight likely to be encountered in the lifetime of a bridge, and hence increases load effects due to one-truck events. It also increases the probability of extremely heavy vehicles meeting other trucks.
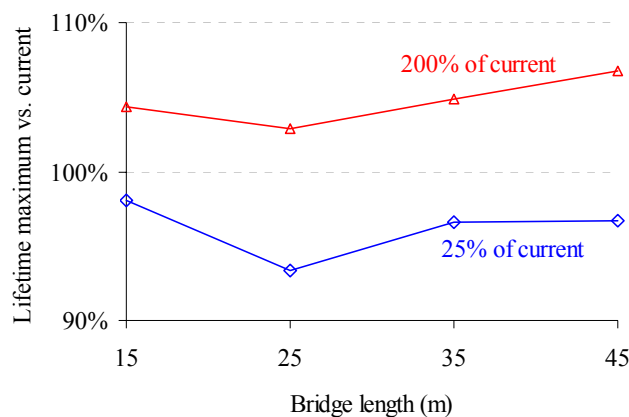

Figure 3   Effect of frequency changes on lifetime maximum bending moment (Czech Republic, high lateral distribution, LE1)

5.2 Limiting maximum weight

Assuming 100% compliance, limiting the maximum permitted GVW has a much greater impact on bridge loading than managing frequencies. The effect is not proportional because, as the maximum permitted weight decreases, events featuring three and four trucks become more important. To evaluate these effects, simulations were performed with different upper limits – 50, 75, 100, 125 and 150 t. Sample results in Figure 4 shows that upper limits of up to 100 t have a significant effect. The non-proportionality can be illustrated by considering that halving the maximum GVW allowed from 150 t to 75 t, or from 100 t to 50 t, gives a reduction in lifetime maximum loading of only 25 to 30%. Restrictions have a slightly greater effect in the Czech Republic because of the longer tail in the GVW distribution at this site. The effect tends to be greater as the span increases because, at shorter spans, it is a combination of axle layout (wheelbase) and GVW that determines loading whereas at longer spans, GVW becomes the dominant factor.

The changing nature of lifetime maximum loading scenarios when weight restrictions are introduced is shown in the examples of Figure 5. This identifies some typical simulated scenarios for traffic at the site in the Czech Republic for hogging moment over the central support of a 35 m bridge. Two cases are shown – (a) with no weight restrictions on current traffic, and (b) a maximum permitted weight of 75 t.
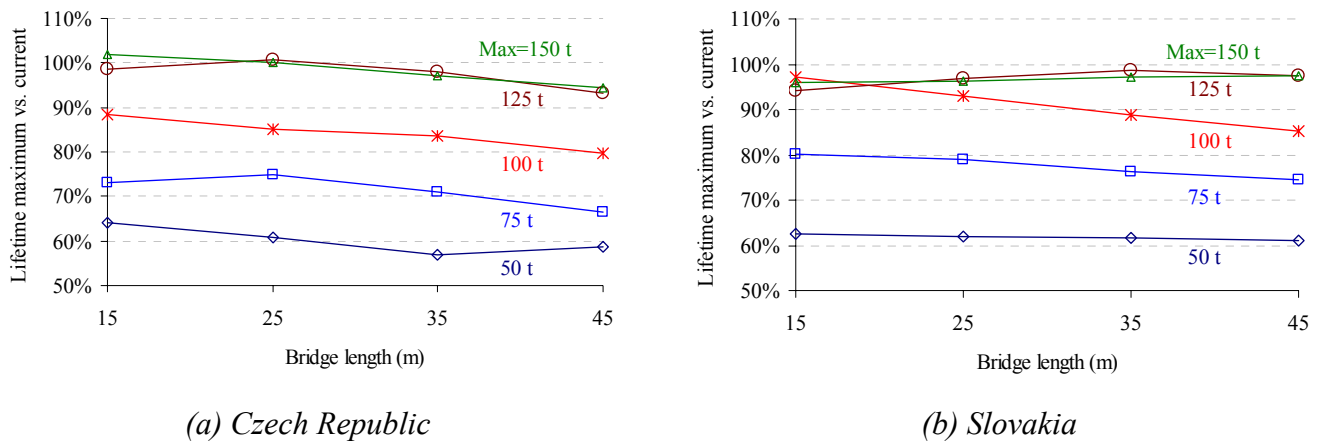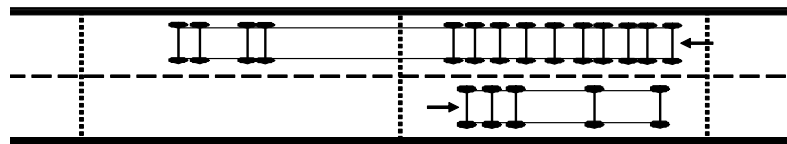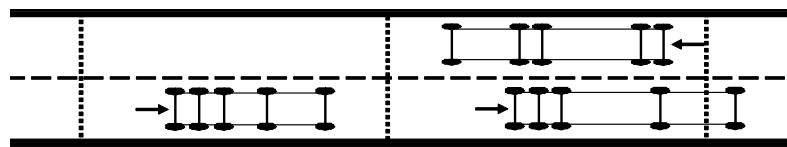
(a) Czech Republic　　　　　　　　　*(b) Slovakia*

Figure 4　Effect of weight management on lifetime maximum bending moment
(Low lateral distribution, LE1)

(a) Current traffic: 157 t 14-axle low-loader meeting 43 t 5-axle truck. Moment= 2541 kNm.

(b) Maximum weight permitted 75 t: 41 t 5-axle truck meeting 37 t 5-axle truck and 69 t 5-axle crane-type vehicle. Moment = 1826 kNm

Figure 5　Effect of weight restrictions on lifetime maximum loading scenarios
(Czech Republic, high lateral distribution, bridge length 35 m, LE4)

5.3　Managing vehicle types

No simple conclusions can be drawn about the effectiveness of controlling the types of vehicles that are given permits. Almost all vehicles over 100 t are either cranes or low loaders, and almost all over 120 t are low loaders. Both types of vehicle have groups of closely-spaced axles with up to eight or nine heavily-loaded axles in the group. The severity of the loading from these vehicles depends on the length and type of bridge, and on the particular load effect being considered.

6.　Conclusions

Lifetime maximum loading on the types of bridge considered here is dominated by extremely heavy special permit vehicles. Limiting the frequency of these vehicles has very little effect on bridge loading. On the other hand, increasing the frequency of permits issued does not, within reason, increase bridge loading significantly. It is difficult to devise simple policies aimed at managing the types of vehicles for which permits are issued although it may be possible, with

further work, to suggest rules for acceptable configurations of groups of heavily-loaded and closely-spaced axles. It is clear that the most effective way of reducing bridge loading is to limit the maximum gross vehicle weight permitted. However, the reduction in bridge loading is not proportional to the reduction in maximum weight as multi-truck loading events become more important as the maximum permitted weight is reduced. The effects on economic activity of limiting maximum weights also need to be considered and may offset, to some extent, the potential savings in infrastructure maintenance.

7.   Acknowledgments

8.   References

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