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Estimating Characteristic Bridge Loads On A Non-Primary Road Network

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ABSTRACT: When collecting truck loading data on a primary road network a common approach is to install a large network of permanent pavement-based Weigh-In-Motion systems. An alternative to this approach would be to use one or more portable Bridge Weigh-In-Motion systems which could be moved between bridges at regular intervals to determine the traffic loading throughout the network. A data collection strategy is needed to put such a system to best use. This paper details the data collection strategies which were examined for the National Roads Authority in Ireland. The use of urban economic concepts including Central Place Theory are discussed as methods for analysing which roads are expected to experience the greatest truck loading.

KEY WORDS: Bridge; Weigh-In-Motion; WIM; B-WIM; Data Collection Strategy; Secondary Roads; Traffic; Loading; Economics; Central Place Theory.

1 INTRODUCTION

A common method for collecting load data on a road network is to install permanent pavement based Weigh-In-Motion (WIM) sensors at a large number of sites on the network. Such a system is expensive and installation and maintenance causes disruption to traffic. An alternative which is less expensive is to use a portable Bridge WIM (B-WIM) system which is moved periodically between bridges on the network. With the recent advances in nothing-on-road axle detection [1] this allows truck loading across the network to be investigated with little or no disruption to traffic. This paper considers the implementation of such a system on a non-primary road network where traffic flows are relatively low.

All roads do not experience the same volumes of truck traffic. Extremely heavy special permit trucks have the greatest influence on a bridge's characteristic load effects. As the number of permit trucks is very small in comparison with regular trucks, in short-term weighing operations they may not be captured in sufficient volumes to provide accurate statistical data. A method of finding roads which experience large volumes of permit trucks is needed to focus random weighing operations across a non-primary road network.

The volumes of regular trucks are also important as the critical bridge loading event may involve a permit truck meeting a regular truck on the bridge. To try and predict the volumes of both truck types, Central Place Theory and other urban economic concepts relating to sector location are examined to identify economic activities which "generate" these trucks. A basic methodology for estimating the volumes of permit trucks on a given road is also formulated.

A strategy for locating sites for the portable B-WIM system is also needed in order to put the system to best use. This strategy allows an accurate estimation of the general truck loading throughout the network as well as the loading on roads which are found to have high probabilities of very heavy permit trucks. The system must also be capable of targeting "problem" areas such as ports, steel manufacturers, etc.

This is not the first time data collection strategies have been considered for determining the location of weighing operations. Data gathered from an extensive WIM network is used in Montana, USA [2] to choose sites for weight enforcement the following year. Methods are developed for processing the WIM data on a month by month basis and determining the areas to be targeted. It is estimated that this targeted enforcement strategy was saving $500,000 a year (2001-2002) in pavement damage. This strategy is not directly comparable however as it is used for locating weight enforcement activities rather than WIM data collection sites.

This paper examines work which was completed for the National Roads Authority (NRA) [3]. The NRA is currently (2012) installing a system of permanent pavement-based WIM sensors on Ireland's major inter-urban roads. These permanent systems will not provide any data on Ireland's non-primary road network. This work investigates the use of a portable B-WIM system to gather data on the 15,000 km of national secondary, regional and legacy national primary roads (i.e., former national primary roads which, although still in use, have been superseded, typically by motorways). These roads will be referred to in this paper collectively as the non-primary road network. As this portable B-WIM system would be moved around the network at regular intervals, a data collection strategy is needed for selecting suitable sites.

2 SOURCES AND DESTINATIONS OF TRUCK TRAFFIC

2.1 Central Place Theory

Central Place Theory was developed by Christaller [4] to explain the location of cities and towns within a region relating to their function. The basis of the theory is that different types of business serve differently sized populations and that these businesses aim to locate at the centre of the population they serve. The size of these market areas vary across different industries. For example, all towns require a grocery store and a butcher shop whereas only larger towns have more specialised functions such as computer stores. The theory generates a hierarchy of central places with the range of goods available increasing with the size of the city/town.

Assuming that there is a boundless homogeneous plain that can be settled uniformly, and that each city/town within the central places hierarchy is equidistant from other cities/towns of similar size, Christaller finds that the only settlement pattern that satisfies these criteria is a hexagonal one - see Figure 1.

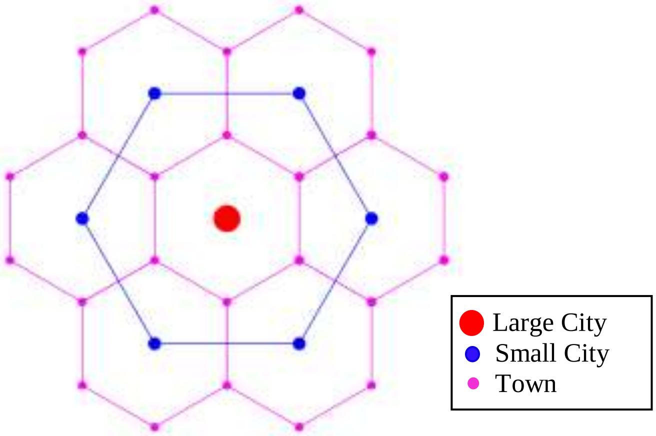

Figure 1. Hexagonal pattern for locating central places.

If this theory is to be used to determine the routes most used by truck traffic, the key is that there are different types of cities with definite patterns of trade between them. Each city/town imports from a larger city/town and exports to a smaller city/town [5]. Cities of similar size are assumed not to trade (clearly a simplification in the theory). While there are clear limitations to Central Place Theory, in particular noting the existence of industrial and other transport intensive uses in out-of-urban locations, it can be adapted to forms a basis for a discussion on the sources and destinations of truck traffic.

2.2 Regular Trucks

When examining bridge loading there are two distinct types of truck, regular and permit. Regular trucks carry mostly consumer goods such as food, furniture, clothes and electrical products between central places. These generally have 2 or 3 axles on a rigid base or a 5 or 6 axle articulated configuration. Although they can be involved in critical bridge loading events they tend not to be the dominant truck in such events. Variations in the weight/frequency of these trucks has only a small influence on the total load effect in critical bridge loading events.

Using Central Place Theory it can be assumed that these trucks are found mainly on the roads connecting larger cities/towns with smaller cities/towns.

2.3 Permit Trucks

Permit trucks are those which exceed the normal legal limits for vehicle weight and/or dimensions. They generally weigh over 40 tonnes and consist of crane-type vehicles or low loaders. Crane-type vehicles - mobile cranes and trucks carrying crane ballast - have heavily loaded closely spaced axles. Low loaders comprise of a tractor unit pulling a trailer and have a single large axle spacing of about 11 m. These trucks are important for hogging moment over an internal support in multi-span continuous bridges.

Permit trucks make up a very small proportion of the overall truck population but they are the dominant vehicle in critical bridge loading events on short to medium span bridges. WIM data from 5 European sites containing 2.4 million trucks are examined and it is found that permit trucks make up an average of 1.63% of the truck population.

Permit trucks are almost entirely related to the construction industry. Over 900 hundred photographs of trucks from a WIM site in the Netherlands are examined. 390 of these are clearly identified as loaded permit trucks. Of these 328, were construction related, the nature of 56 could not be conclusively identified and 6 were found to be non-construction related. The non-construction related trucks were carrying boats and buses.

Construction is associated with areas which are experiencing economic growth. As the wealth of an urban or city region grows, new domestic and commercial buildings need to be constructed [5] as well as new infrastructure such as bridges, roads and tunnels. It is these construction projects that are the main destinations for permit trucks. It is assumed that, unlike regular freight movement, construction traffic is then not directly proportional to the size of nearby cities but rather proportional to both size of the city/town and its economic growth. Regular trucks, on the other hand, are associated with trade and their number can be reasonably assumed to be proportional to city size. The ratio of regular trucks to permit trucks is then not constant and varies depending on economic growth. At the five European WIM sites, the percentage of permit trucks is not constant and varies between 0.74% and 2.71%. However, it is unclear whether or not this is due to economic growth in nearby cities.

The destinations of permit trucks are generally cities experiencing economic growth but they could also be travelling to other locations dispersed throughout a country or region. For example roads, tunnels and railways are constructed between cities and other once off developments such as wind turbines, power plants and cement factories are usually located away from large towns and cities.

The sources of permit trucks are also more dispersed than the sources of regular trucks. Large scale manufacturing facilities - which can require large areas of land - are often located away from large cities where land is expensive. Permit trucks can also originate from a port. The various origins and destinations of these permit trucks suggest that many of them use the non-primary road network for at least part of their journey.

The conclusion then is that most permit trucks are travelling from anywhere to a city/town experiencing economic growth and a lesser percentage travel from anywhere in the country to anywhere else. The relative probability of a permit truck occurring at any location on the non-primary road network can then be calculated and decreases from a maximum near cities experiencing high levels of economic growth to a minimum background level at the furthest distances from these cities. This needs to be taken into account when designing a data collection strategy for a portable B-WIM system on the non-primary road network.

3 REVIEW OF IRISH ROAD NETWORK

The methods outlined in Section 3 and 4 are similar to those described in a previous paper by some of the same authors [6].

The non-primary road network in County Kildare is examined to get an idea of the number of bridges throughout Ireland which are suitable for B-WIM. An NRA database is used to examine the bridges on legacy national primary and national secondary roads. As no such database is available for regional roads, a site visit was made to a number of these roads and their bridges surveyed - see Figure 2.

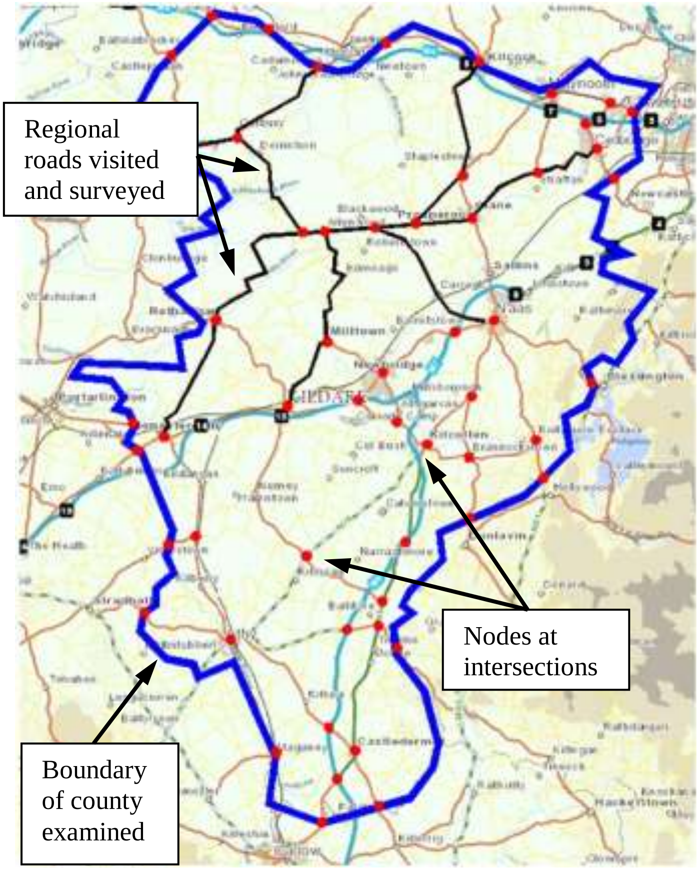

Figure 2 – County Kildare showing regional roads surveyed and nodes at intersections of relevant roads

3.1 Suitability for B-WIM

The suitability of a bridge for B-WIM [7] is assessed using four criteria:

1. **Construction material:** Steel or iron is best but reinforced concrete bridges can also be used. Masonry and other arched bridges were deemed unsuitable.
2. **Access:** Soffit of the bridge must be accessible. Bridges located over fast flowing rivers or busy roads/railways were deemed unsuitable.
3. **Span:** Short, simply supported, spans are preferred but continuous bridges can also be used.
4. **Skew:** Ideally the bridges should not be skewed although some skew can be allowed for in the B-WIM software.

Using the four criteria listed above, the suitability of bridges for a B-WIM system, was assessed and bridges divided into the following categories:

Category 0: Not Feasible – Bridge not suitable for B-WIM installation

Category 1: Feasible – Possible to install system, but with some complications

Category 2: Ideal – System could easily be installed on this bridge

3.2 Suitability of Irish Bridges

Tables 1 and 2 provide summary information on the bridges examined and their suitability for B-WIM. Ireland has a relatively high proportion of masonry arch bridges [9], which are unsuitable for B-WIM. The proportion of B-WIM suitable bridges in countries with fewer masonry arch bridges may to be higher than in Ireland. Photographs of bridges in each of the three categories are provided in Figure 3.

Table 1 - Summary of bridges on each road type examined and suitability for B-WIM

Road Type	Length (km) Examined	No. of Bridges	Cat. 0	Cat. 1	Cat. 2
Legacy	116	41	34	5	2
Secondary	62	47	39	6	2
Regional	122	44	36	7	1

Table 2 - Suitability of bridges examined for B-WIM system

Road Type	% Suitable for B-WIM (Cat. 1 or 2)	Average Distance Between Suitable Bridges (km)
Legacy	17	17
Secondary	17	8
Regional	18	15

(a) Category 0 (not feasible)

(b) Category 1 (feasible)

(c) Category 2 (ideal)

Figure 3 – Samples of the bridges examined

4 DATA COLLECTION METHODS

Data collection methods for selecting the roads on which the portable B-WIM system is installed are examined. The aim is to cover the entire non-primary road network with a focus on roads which are expected to experience high volumes of permit trucks.

4.1 Length Method

Every road in the network has a road number. The length method uses these numbers to identify the roads in the network and then each of these roads is divided into sections of about 15 km in length. A section of road is picked randomly – with equal probability of all such sections being selected – and the B-WIM system installed on a suitable bridge on this section of road. If a suitable bridge is not available on that section, then the nearest suitable bridge on the same road is used. The B-WIM system is left at each site for a week before being moved to another randomly chosen section of road. Sections with a higher probability of permit trucks could be weighted to increase their probability of being selected. An installation period of a week was chosen so the system could measure vehicle weights on many different roads and a general picture of the loading on the entire road network could be obtained.

The average distance between suitable bridges - shown in Table 2 - suggests that a majority of the sections selected should either contain a suitable bridge or be reasonably close to one.

Once a section of road has been chosen it is either excluded from future selections or included. If it is excluded:

- Every section of road in the country is covered in a fixed time.
- Existing sources of heavy loads that repeatedly use the same roads are found in that fixed time.
- If a new source of heavy loading emerges on a route that has already been picked, it cannot be detected until the cycle of all roads is complete.

If selected road sections are included as candidates for future selection:

- It is not possible to guarantee that every section of road in the country is selected in a fixed time period.
- New and emerging sources of heavy loads are just as likely to be selected as existing sources.

Given the extremely long cycle to cover all sections - 20 years based on an estimated 15,000 km of roads - the latter approach is recommended. It is also recommended that the selection of road sections should take account of their relative probability of the truck traffic containing permit trucks.

4.2 Node Method

This method uses nodes to divide up all the roads being examined into segments. A node is located at each intersection of these roads. The network is then divided up into sections, with each section beginning at one node and finishing at the next node encountered. Sections are then randomly chosen and the B-WIM system installed on a suitable bridge on this section of road. If no suitable bridge is found then another section is randomly chosen. As with the length method, sections with a higher probability of permit trucks could be weighted to increase their probability of being selected. This method was applied to County Kildare and 56 nodes were found – see Figure 2 – which resulted in 75 sections of road. Assuming that each of the 26 counties of Ireland contains the same number of road sections, we get an approximation of 1,950 road sections for the whole country.

Large loads travel the full length of sections of road between pairs of nodes, with the exception of the sections at the beginning and end of their journey. The aim of this method then is to divide the network into stretches of road which experience near uniform loading. The disadvantage of this method is that it results in more road sections than the length method and it would take nearly twice as long to examine every section in the country. These sections of road also tend to be short, with lengths varying between about 2.5 km and 15 km, based on the data collected for the county examined. Therefore when a short section is chosen it is unlikely to contain a suitable bridge, which leads to some inconsistencies.

4.3 Targeted Data Collection

This method uses the portable B-WIM system to solely target known or perceived sources of heavy loads. The system is moved around the country on a weekly basis or as required, between areas that were identified as likely to experience illegally overloaded vehicles. If overloaded vehicles are detected on a road, the police could then be asked to target this route and set up checkpoints or to visit repeat offenders. There is some anecdotal evidence that this kind of approach is working well elsewhere in Europe. Sources of overloading may include:

- Precast concrete manufacturers
- Steel suppliers/manufacturers
- Logging areas and sawmills
- Ports
- Crane suppliers/manufacturers

A targeted data collection approach could also be used to examine sections of road:

- Where abnormal road surface deterioration is experienced. Such roads may be identified using local knowledge or by comparing yearly road roughness data.
- With high ADTT.
- Which are alternatives to tolled motorways.
- Where there is concern about the condition of a particular bridge.
- Which are close to a known source of, or destination for, heavy vehicles.

The advantage of this method is that it is much more likely to capture extreme events than the length and node methods. The disadvantage is that the data collected is biased and does not give an indication the underlying general trend on the road network.

4.4 Case Study

A hypothetical scenario is created, and each of these methods is applied to it, in order to assess their ability to capture extreme loading events. The scenario considers that a destination of heavy vehicles emerges in Cavan Town and that, once a week, a very heavy permit truck travels from Athlone to Cavan (see Figure 4). It is assumed that this journey occurs once a week for one year. The route is chosen as it does not contain any inter-urban roads and uses only roads on the non-primary road network. It covers 81 km of regional and national secondary roads. It is assumed that a single portable B-WIM system is used to cover all 26 counties in the Irish non-primary road network.

Figure 4 – Hypothetical route examined - route highlighted and nodes shown

4.4.1 Length Method

As the route covers 81 km of road, it contains 5.4 (81/15) road sections according to the length method. Based on an estimated total length of 15,000 km, there are 1,000 segments of road in the country. The probability of successfully capturing the event at least once in one year (50 working weeks) is calculated from basic probability concepts [10] using Equation (1):

$$\text{P(Capturing Event)} = p + qp + q^2p + q^3p + ... + q^{49}p \quad (1)$$

where: p = the probability of any of the 5.4 sections being measured in a given week
q = the probability of one of the sections not being measured in a given week

Using Equation (1), the probability of this Athlone/Cavan event being captured by the length method is 23.7%.

4.4.2 Node Method

The route in question was found to contain 10 road segments – see Figure 4. For the purposes of this study, the crude assumption is made that each of these road segments contains a suitable bridge. In reality it is unlikely that this would be the case. It is also estimated, by extrapolating from the county examined, that there are 1950 road sections in the country. The probability of this event being captured by the node method is then calculated as 22.7%.

4.4.3 Mixed Targeted and Random Approach

The random (length and node) methods give better statistical information on the complete distribution of loading in the target network. Targeting likely locations of overload on the other hand is statistically biased – the data collected tends to represent the upper end of the true loading distribution and its use could result in excessive conservatism in pavement design or bridge assessment. However, targeting has the advantage that it may result in a reduction in the extent of overloading which saves costs in the pavement maintenance budget in particular. A compromise between these two approaches is to divide the B-WIM system equally between random and targeted approaches. Assuming that the hypothetical event is not among the routes targeted, the probability of it being detected is reduced to 12.7% for the length method or 12.1% for the node method. Doubling the number of B-WIM systems would result in nearly double the probability of success while also allowing one sensor to be permanently used for the targeted approach.

5 CONCLUSIONS AND RECOMMENDATIONS

Central Place Theory and related concepts to economic growth are presented here as a framework for determining the origins and destinations of regular and special permit trucks. Construction is identified as a key source of permit trucks, which are the dominant vehicle in extreme bridge loading events. Economic growth is presented as a generator of permit truck movements. Regular trucks - whose movements can be predicted using Central Place Theory - play a minor role in these extreme events.

Two different data collection strategies for determining sites for portable B-WIM operations on a non-primary road network are examined. Both methods perform similarly in the case study, i.e., each gives a similar probability of detecting the repeated overloading scenario. The length method is recommended as it is more straightforward to implement than the node method. It is also recommended that repeat selections be allowed in order to avoid problems associated with the long cycle required.

In order to overcome some of the shortfalls of the methods, which are discussed in Section 4, it is recommended that the B-WIM system operate the length method for half the time and be used for targeted data collection for the other half. This allows the loading conditions on the non-primary road network to be examined while also targeting problem areas.

A permanent WIM installation and a portable B-WIM system have similar capital costs. As the data collection strategy proposed here requires weekly reinstallations and recalibrations it will have significantly higher operational costs than a single permanent system. However, if the aim is to cover an entire non-primary road network then the portable B-WIM proposal offers a significant cost advantage over a network of permanent systems.

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