Inferring Asset Live Load Distributions from Traffic Flow Data: A New SHM Opportunity?

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INFERRING ASSET LIVE LOAD DISTRIBUTIONS FROM TRAFFIC FLOW DATA: A NEW SHM OPPORTUNITY?

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ABSTRACT

With the continuous ageing of infrastructures, live load distributions related to actual traffic has become one of the key inputs in asset management. However, it is also one fraught with difficulty, due to its complex and dynamic nature, which can only be addressed at a network level. At this level, it is impossible to envisage in-situ SHM systems installed for all critical assets. In this context, the development of reliable alternative techniques to estimate live load distributions would be a valuable addition to infrastructure asset management tools. As is well known, the accuracy of such estimates depends on several factors such as road capacity, asset condition/performance, traffic composition and seasonal effects, among others. Thus, the deployment of in-situ asset-specific systems needs to be complemented with other types of monitoring systems based on inexpensive and easy to install traffic flow sensors (point and line) in order to infer, with acceptable accuracy, rather than measure directly the live load distributions pertinent to different asset types on the network.

This paper presents an approach to derive load distributions based on a *Transport Infrastructure Utilisation and Maintenance Framework* by utilizing recent advances achieved in two, often non-communicating, fields: structural engineering and transportation engineering. From the realm of transport analysis, the parameter 'flow' has been combined with the parameter 'live load' pertinent to structural performance. Taking advantage of traffic flow sensor systems, the aim is to examine how information related to the former enables the understanding and modelling of the latter, thus paving the way for smart transport mobility technology to be harnessed by the structural asset management community.

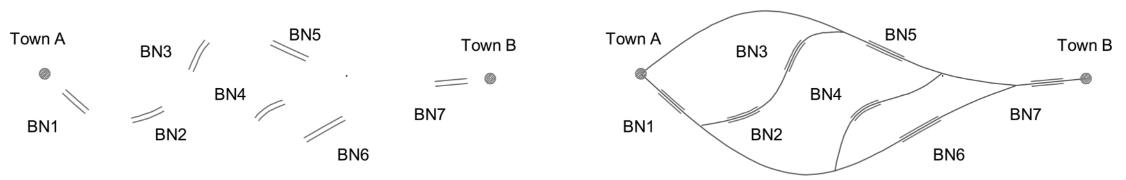
KEYWORDS : *Asset management, Probabilistic methods, Transportation networks, Structural Health Monitoring.*

INTRODUCTION

Over the past century, European countries have developed mature and extensive transport infrastructure networks, allowing people and business to prosper. They include many complex and intensely used routes, which have to be maintained, upgraded and expanded in the coming years. Indeed, both governments and owners realise that society's dependency on infrastructures will intensify over the next generations, with a number of key drivers having a long term impact on future needs across all sectors, such as obsolescence, globalisation, growing demand, climate change and interdependence [1]. In response, for the past two decades, the building blocks leading to successful application of integrated asset management tools are being put in place. Key developments and innovations in this sustained effort focus on how structural sensors and health monitoring technologies might contribute to the improvement of intelligent transportation systems for operational monitoring and incident detection [2].

In every network there are critical components, sometimes referred to as the *bottlenecks* (BN) of the system [3], which, in the case of transportation networks, correspond to bridges, tunnels and dams, these assets being most vulnerable if the network is exposed to either natural or anthropogenic hazards. Indeed, these structures are of great importance taking into account that through them several infrastructural functions are normally distributed, e.g. a road, a railway track, a subway track, electrical and gas lines, etc. For example, if a bridge is damaged/removed, the areas on each side of the bridge become disconnected and the infrastructure functions between these areas are disrupted [4]. Therefore, it is very important that these assets preserve a degree of their functionality throughout their life cycle, even in the case of extreme events.

Figure 1 illustrates this issue: while on the left the assets, the bottlenecks *BN*, are treated as isolated systems, on the right the existence of links alters the perspective of the problem. For example, considering a travel demand from Town A to Town B, then: (i) if *BN1* fails, it will lead to an increase in the traffic flow over *BN5*; (ii) if *BN7* fails, the connectivity between Town A and Town B is compromised; (iii) if *BN4* and *BN7* were identical in terms of their structural performance, the failure of *BN7* has a much greater impact on the network functionality compared to the failure of *BN4*. All issues described above, derive from the fact that the bridges are embedded in a network that implies a dependent behaviour between all its critical elements. Consequently, a broader approach to asset management that involves both structural engineers and transportation engineers has the potential to yield substantial benefits.



a) assets as isolated components b) assets as components of a network system

Figure 1 : Transportation Infrastructure Systems.

Currently, a truly holistic approach for optimal asset management that considers the network perspective is still missing because different perspectives need to be merged into a unified framework [3]. At this level, analysis of a decomposed sub-system of a complex network does not necessarily give an objective indication as to the behaviour of the whole. When dealing with a system of isolated components), the problems are normally solved based on very well defined and validated theoretical models that simulate the physical and material/mechanical behaviours. Normally, parameters such as deformations, stresses, deflections, and bending moment diagrams support the assessment of the safety level [5]. However, when dealing with a network subjected to a certain travel demand scenario, the main variables of the problem change to connectivity, vulnerability, robustness and resilience [6, 7]. It is, therefore, evident that there is a layer missing between these two levels of analysis: the analysis of assets as isolated structural systems and the analysis of the same assets as potential *bottlenecks* in a transportation network.

1 TRANSPORT INFRASTRUCTURE UTILISATION AND MAINTENANCE FRAMEWORK

Asset management is defined by Haas et al. [8] as: *a set of tools or methods that assist decision makers in finding optimum strategies for providing and maintaining infrastructure in a serviceable condition over a given period of time*. Furthermore, it is often the case that transport assets remain in service for much longer than pre-determined life cycles. For example, considering highway assets life cycle ranges from 20-100 years [9], the majority of UK's motorways have been in service since the early 1960's, with several assets exceeding their designed life cycle. Other networks, such as the London Underground have been in service for well over 100 years, utilizing tunnelling infrastructure built in the 1860's. Evidence of such long service periods emphasizes the importance of up to date asset management tools.

Inspired by the work of Gómez in [10], a *Transport Infrastructure Utilisation and Maintenance Framework, TrIUMF*, is proposed based on the idea that through a modular representation, it is possible to identify subsystems and form explicit relationships at every level through a set of input/output variables (Figure 2). This provides the means to identify processes, properties and characteristics at different levels of granularity. This framework focuses on the identification of the type and time of transport asset management needs, so that the cost of maintenance over a period is minimized while acceptable serviceability standards are met. In this context, two horizontal layers are conceptualised: (i) *Asset level* and (ii) *Network level*. Additionally, four vertical layers are identified: (i) *Physical Models* that contain the performance and flow assignment models feeding information to each other and setting the backbone of the framework by integrating structural and transportation engineering; (ii) *Thresholds* that contain the indices and respective range of acceptance, which allow the evaluation of the asset performance (e.g. concrete cracking, fatigue) and the *network* performance (e.g. accessibility, satisfy demand). (iii) *Management Options* that contain maintenance, traffic and monitoring options, whose implementation would ensure that the thresholds are not violated during the life cycle. (iv) *Cost-benefit Analysis* that contains the elements of cost and benefit associated with various maintenance, traffic and monitoring options, in order to formulate the objective function of the problem to be solved.

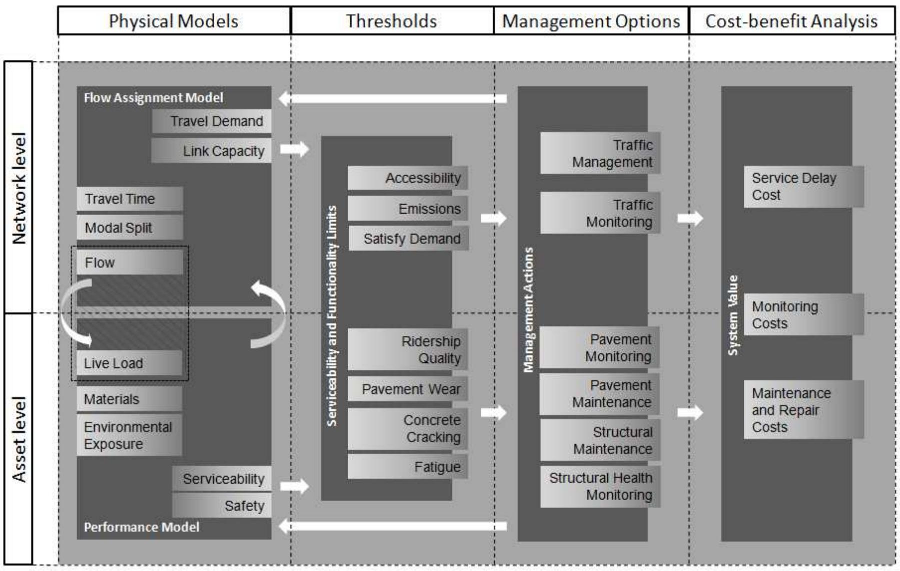


Figure 2: Transport Infrastructure Utilisation and Maintenance Framework (TrIUMF).

An important feature of the proposed framework is that asset and network levels are, as far as possible, self-contained in terms of their formulation but linked in terms of input/output variables. Therefore, it has the ability to examine both: (i) short-term impacts through the optimization of traffic travel times and (ii) long-term impacts through the optimization of asset performance.

2 INFERRING LIVE LOAD DISTRIBUTIONS FROM TRAFFIC FLOW DATA

The *TrIUMF* framework raises a plethora of scientific research questions, however the accuracy and relevance of the results is particularly sensitive to the interaction of the physical models. On one hand, the flow assignment model assigns flow to network paths depending on travel demand and link capacity; whereas, on the other, the serviceability/safety of assets is calculated using performance models dependent on the applied live loads. In this context, and taking into account the intrinsic relation between traffic flow and live loads, the cycle (Figure 2) *link capacity > (traffic flow assignment model) > flow > live load > (asset performance model) > serviceability / safety* lies at the centre of the framework. Although, the relationships between *capacity* and *flow* and *live load* and *serviceability/ safety* are examined in depth in transport and structural engineering literature respectively, the accurate evaluation of *live loads* from *traffic flow* remains relatively unexplored.

2.1 Traffic flow

Modelling of transportation networks can be implemented at various detail levels such as micro-, meso- and macro-scopic, each providing a unique insight to network operations. Microscopic models are ideal for dealing with problems such as queue length, traffic signals control and infrastructure design, when it is necessary to evaluate accurately the maximum capacity and impact of local road traffic on such network sections. However, the development of extensive traffic measurement systems installed in major urban areas and motorways encouraged the development of macroscopic models, in which traffic is commonly measured in terms of flow, density and average speed. At an intermediate level of detail, mesoscopic models deal with vehicles grouped into packets, which act as single entities and are then routed through the network [11]. The modelling choice depends primarily on the scale of the network, the availability of traffic data and the scope of the analysis undertaken.

When the focus is to examine the performance at a network level, macroscopic models can be more efficient. At this level, more aggregated properties of traffic are tracked such as flow, q, (the number of vehicles that pass a certain cross-section in the network during a unit of time), density, k (the number of vehicles per distance unit) and traffic speed, which can be defined in a collective level as an average value over time, time-mean speed, or over space, space-mean speed. Based on these parameters, the three-way relation between flow, density, and space-mean-speed defines the fundamental principles of traffic flow theory [6], which assumes that (i) speed and density are linear inversely proportional; (ii) density and flow increase proportionally until maximum flow is reached, henceforth, as more vehicles are added into the network, density increases but flow decreases because the network becomes congested and vehicles travel at a lower speed and; (iii) speed reduces proportionally to increasing flow when the network is in free-flow uncongested conditions; However, once the maximum flow is reached, flow and the speed will decrease together leading to a traffic jam, as density increases.

Normally, macroscopic models are preferred due to the ease of gathering aggregated traffic data, which benefits from the continuous advances on the functionality of traffic monitoring systems, i.e. more accurate and complete data. Table 1 summarises the most common traffic monitoring systems used for traffic data collection.

Table 1: Traffic monitoring systems.

System	Advantages	Disadvantages
Pneumatic tubes	Measure traffic flow, direction and speed Categorise vehicles in broad classes, i.e. cars, buses and heavy goods vehicles	No weight estimation
Inductive loops	Low installation and maintenance cost Widely used	No weight estimation
Radar detectors	Light and discrete equipment No installation on the pavement	No weight estimation
Manual traffic-counting	Location robustness	Labour intensive No weight estimation

The organization of the collected data can differ depending on the measurement system used. In the case of manual traffic-counting, data is usually grouped into broader categories such as cars, vans and trucks because is labour intensive. However, a more detailed classification can be achieved by other systems. For example, the Federal Highway Administration in the USA has published Vehicle Classifications based on 13 vehicle classes (from motorcycles to multi-trailer 7 or more-axle trucks) using data collected by pneumatic tubes [12].

2.2 Live loads

When a vehicle crosses a bridge, it may or may not cause a measurable structural effect. The reason for this is that bridges are designed according to serviceability and safety limits that are associated with non-frequent / rare live load events. This implies that although the entire spectrum of the traffic flow composition is important from a transportation engineering point of view (travel time, modal split), the loads associated with heavy vehicles or specific events such as traffic jams are most relevant from a structural point of view (serviceability, safety). Several works can be found in the literature focussing on the knowledge of effective live loads, mainly extreme loads, and their structural effect on bridges. Interestingly, these works are generally supported by data collected by Weight-In-Motion (WIM) systems. Table 2 summarises the main established and available WIM systems used for measuring traffic loads, which offer a variety of accuracy levels for different costs.

Table 2: WIM systems.

System	Advantages	Disadvantages
Bridge-WIM	Exceptionally durable Invisible to the drivers Installation/replacement without requiring traffic disruption Redundancy of recordings Allow bridge assessments Extreme loads can be accurately quantified	High costs of installation Dependent on bridge location Require calibration (each bridge is different from the others). Require expert technicians Dependent on vehicle position, length of the structure and the traffic density
Load cells	Highly accurate Direct measurement of loads Fully automated weighing system Can weigh all vehicle types regardless speed or axle configuration	High equipment, installation and maintenance costs. Require civil engineering work and can cause damage to the pavement Require a concrete foundation.
Bending plates	Good accuracy Fully automated weighing system Can weigh all vehicle types regardless speed or axle configuration Get full tire imprint	High installation costs Require a large amount of civil engineering work and can cause damage to the pavement Require a concrete foundation Sensitive to temperature effects
Strip sensors	Cheaper solution, mainly regarding the installation costs Requires less civil engineering work for installation	Do not measure directly the wheel/axle load High equipment/maintenance costs Sensitive to temperature effects and pavement characteristics
Multiple sensors	Improved accuracy when compared with one-sensor-based systems	Accuracy depends on the number/spacing of sensors

Initially, WIM in Europe was used for law enforcement concerning overloaded vehicles, with the underlying European Commission goal of ensuring fair competition between transport modes and transport companies [13, 14]. Nowadays, WIM is a reality across several countries, such as Poland [15], Lithuania [16], France, Slovenia, Hungary and Netherlands [17].

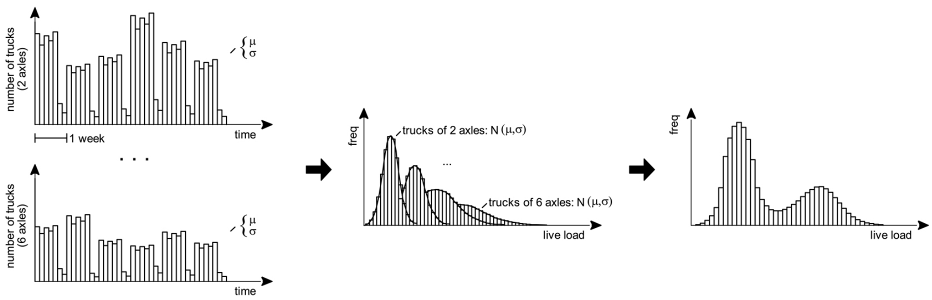
Even so, it is well known that these solutions are expensive and in order to guarantee the systems' reliability they require periodical maintenance / replacement. Moreover, it is financially infeasible to have WIM in all links of a network thus, they need to be complemented with other types of monitoring systems that, ideally, are inexpensive and easy to install. It seems reasonable that a valid strategy is to combine WIM systems with traffic monitoring systems (Table 1 and Table 2). Indeed, this makes perfect sense at the transportation network level, as live loads could be inferred from data collected by traffic flow systems encompassing most links, whereas direct measurements of live loads, mainly through WIM systems, would be performed selectively in some of the *bottlenecks* of the network.

2.3 Methodology to infer live load from traffic flow data

Gross Vehicle Weight, GVW, is defined as the maximum legally permitted weight of the vehicle plus load, which is usually grouped by truck-axle classes. As an example, Table 3 shows the maximum allowable GVW according to information from the House of Commons Library in the UK [18]. Interestingly, information based on surveys is becoming available with respect to the effective live loads on transportation networks, mainly the characterization of empty vehicle weight and GVW. As a reliable and up-to-date example, a detailed survey can be found on the Swedish HGV fleet in 2013 [19]. The available data make possible the statistical characterization of the live load distribution associated with each truck-axle class, in an independent mode. In this context, it seems reasonable to consider that the relationship between traffic flow and live loads can be set based on the number of trucks (traffic flow) and statistical information related to the GVW (live load), for each truck-axle class. Indeed, several authors claim that GVW data are consistent with the multimodal, in most cases Normal distributions, $N(\mu,\sigma)$ [20, 21]. This supports a key tenet of the suggested approach, namely to explore the GVW histogram as an addition of several elementary histograms, each one associated with a truck-axle class. Figure 3 illustrates the proposed methodology to infer live load distributions based on traffic flow information, coupled with truck characteristics for each axle group.

Table 3: Maximum allowable GVW, UK [18].

Number of axles (trucks)	Maximum GVW
2	18 t
3	26 t
4	32 to 36 t
5	40 t
6	41 to 44 t



a) traffic flow data b) individual class histograms c) combined histogram

Figure 3: Methodology to infer truck loads based on traffic flow.

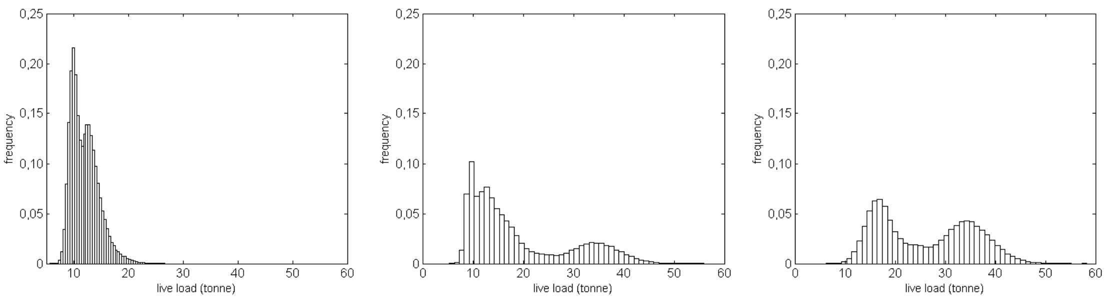
2.4 Exploratory example

In order to illustrate the potential use of the proposed methodology, Table 4 shows a hypothetical sample gathered from a traffic monitoring system (Table 1) and pertinent information related to the statistical characterization associated with the weight of trucks. It is worth mentioning that, although hypothetical, the values chosen are based on information found in the literature [18, 19, 22].

Three scenarios were explored, in order to access the flexibility exhibited by the proposed methodology, mainly: (i) all trucks are empty, (ii) all trucks are fully loaded and (iii) There is an equal chance that trucks will be fully loaded or empty. Figure 4 shows the final live load histograms, taking as input the data presented in Table 4.

Table 4: Traffic flow and GVW data.

Number of axles (class identifier)	Class frequency	Empty		GVW	
		μ	σ	μ	σ
2	40. 0 %	10.0	0.8	17.0	2.5
3	12.5 %	12.5	1.0	24.0	3.0
4	20.0 %	13.0	1.5	33.0	3.5
5	22.5 %	14.0	2.0	36.5	4.0
6	0.5 %	17.5	2.5	40.0	4.5



a) all empty b) 50% empty - 50% GVW c) all GVW

Figure 4: Estimation of truck load histograms.

Generally, the methodology is able to capture the multimodal behaviour of the truck loads associated with traffic loads, excepting for the case where all vehicles are considered empty. This is mainly explained by the narrow range of loads associated with this case (3rd column of Table 4). What is more interesting to observe is that, for the opposite case where all vehicles are loaded, the live load histogram shape has a clearly two-modal form. It would be supposed to assume that this was due to the contribution of empty trucks (for the first modal) and fully loaded trucks (for the second modal) however, this is not true. Even for the case of only fully loaded trucks, a multimodal shape is expected, mainly explained by the large range of loads associated (4th column of Table 4). Based on this simple exploratory example, the proposed methodology opens a new perspective on how truck load histograms might be interpreted and utilised. In order to take this a step further, for example for the case of bridges, the truck load distributions will be combined with information related to type and span, which are factors that influence the nature of extreme event that is critical for each structure (e.g. free flow or traffic jam) and the dynamic amplification factor that needs to incorporated into the truck loads.

CONCLUSION

This work presents a novel approach devoted to the optimization of asset and traffic management, by utilizing recent advances achieved in two, often non-communicating, fields: structural engineering and transportation engineering.

A *Transport Infrastructure Utilisation and Maintenance Framework* is presented, and among the several challenges that need to be tackled to put it in practice, a methodology is proposed to tackle the central issue of inferring live loads from traffic flows. Preliminary results obtained for the live load histograms are comparable with those obtained directly by WIM systems. Moreover, the influence of different factors that have a bearing on the shape of these histograms can be explained based on the proposed methodology. This can lead to new knowledge about the effective live load distributions on transportation networks. Further research is required, regarding the statistical characterization of the empty and fully loaded trucks and the possibility of obtaining this information on a continuous basis at different network locations through inexpensive and spatially distributed sensors. Calibration of the approach through selective WIM-based live load distributions is another task that would add value to the proposed methodology.

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