Empirical Distributions of Traffic Loads from Italian Weigh-in-Motion Data

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ABSTRACT: Design actions for bridges, at the state-of-the-art, are based on a probabilistic characterization of traffic loads. Such characterization can be performed with the use of weigh-in-motion (WIM) systems, whose data can constitute a frequentist representation of traffic loads. However, the availability of appropriate WIM data is not widespread, and what data can be found in the literature is not recent. Due to structural safety reasons, the 52 km long A3 highway in Italy, connecting the city of Naples and Salerno, has been equipped with a WIM system which has been operational since the beginning of 2021. The main purpose of this system is to enable a level of traffic control that would impede overloads on the highway’s many bridges. The present article is based on data collected over a year’s worth of uninterrupted operation of the WIM system, during which time more than thirty-six million vehicle transit datapoints were collected. This short paper presents and discusses these WIM measurements, which are filtered and stratified to derive empirical distributions of traffic loads, in terms of gross vehicle weights and axle loads.

1. INTRODUCTION
In state-of-the-art structural codes (AASHTO, 2020; CEN, 2003), traffic loads for the structural safety assessment of new and existing bridges are typically based on semi-probabilistic approaches (OBrien et al., 2015; Wiśniewski et al., 2012). This entails the premise that, for any time interval of interest, the exceedance probability of the effects of these loads on structures (structural actions), can be maintained under control, in principle. Thus, to determine the safety margins under which a bridge operates, so as to introduce traffic control measures and/or structural
retrofitting actions, careful load calibration is needed. Currently, this has special relevance for Italy, where strict rules are being enforced for the operability of road bridges, based on conventional structural safety checks (CS.LL.PP., 2020).

Direct traffic observations represent the straightforward approach to empirically analyze traffic loads with the purpose to derive load models, something that could be also achieved via traffic micro-simulations (e.g., Testa et al. 2022). Empirical measurement of traffic structural actions requires weigh-in-motion (WIM) systems to be continuously operational for long periods of time, in order to ensure that traffic load models based on said data are adequately representative of the circulating vehicle population. In fact, while the EN-1991-2 load model calibration studies started off with availability of traffic monitoring and WIM data for several European highways, the conclusion was eventually reached that only a fraction of those records contained sufficiently detailed vehicle geometry, speed, and axle load characteristics on multiple lanes, to be deemed an appropriate basis for meaningful traffic simulations (Mathieu et al., 1994). This highlights the importance of traffic data availability carrying sufficient information to render them fit-for-purpose with respect to engineering applications.

In this context, as a case-study, one year’s worth of data from the WIM system installed on the A3 – Napoli-Pompeii-Salerno highway in southern Italy are presented and analyzed. These data have been also made available for further research and applications. The A3 is a busy infrastructure connecting the two major cities of the Campania region. It directly links the ports of Naples and Salerno, which are among the most important in the Mediterranean Sea and provides access to the Sorrento and Amalfi coasts. Between 2021 and 2022 the WIM system recorded some millions (36,359,127) of vehicle passages, in the framework of a comprehensive traffic control campaign, meant to avoid overloads on the bridges. These data (Iervolino et al., 2023), have been analyzed in the study presented herein, where the empirical distributions of vehicle weight, axle number, geometry, and other features have been derived.

The remainder of this short paper is structured such that the A3 highway is briefly introduced first and then its weigh in motion system is described. Subsequently, the analyzed data are introduced and analyzed to determine the database for further analysis. Finally, the empirical distributions derived are presented and their potential engineering applications discussed. Some final remarks conclude this work.

2. NAPOLI-POMPEI-SALERNO HIGHWAY
The A3 Napoli-Pompeii-Salerno highway, which is schematically shown in Figure 1, is only 52 km long yet has played a decisive role in the development of the about thirty municipalities situated in the areas around Mt. Vesuvius and the Sorrento peninsula. The first tract, from Naples to Pompeii, was opened to the public in 1928, while a second section, from Pompei to Salerno, was completed in the early sixties. The A3 highway provides services to about eight-hundred-thousand inhabitants and alleviates traffic in the eastern area of Naples’ hinterland. It connects an area which is among the most densely populated in the world and provides supply for the touristic mobility demand generated by archaeological, natural, and religious assets (Pompeii, Herculaneum, Sorrento, Positano, Vietri and Amalfi Coast, Sanctuary of Pompeii, etc.). It also connects the ports of Naples and Salerno, which are among the most important in Europe for shipping commodities. It is part of the E45 European route and links to other major Italian highways A1 (Autostrada del Sole) to the north and A2 (Autostrada del Mediterraneo) to the south. In 2017 the average daily transits on the highway were about a hundred and seventy thousand, for a total of more than sixty million in one year. The 2022 data (to follow) show about thirty-six million transits in one year, that is a daily average of about one-hundred thousand. The A3 has three lanes per traffic direction for most of its length, and part of the segment between Pompei and Salerno crosses several valleys,
overlooking a majestic seacoast. Thus, the tract between the town of Cava de’ Tirreni and Salerno, features several viaducts of various structural typologies. Most noteworthy among those, from a structural engineering point of view, are reinforced concrete stiff deck and slender arch bridges, that is, bridges of the so-called Maillart type (Billington, 1973). Many of these bridges were built based on Swiss design in the fifties, and were chosen, among other reasons, for their elegant appearance.

Several of the bridges on that segment had been found not fulfilling the safety verifications criteria according to the current Italian building code (Crisci et al., 2022). This is not surprising, as most of these bridges were designed several decades ago, with standards, simplified design models, and loads, which can be now considered obsolete. This motivated the installation of a traffic control system, including WIM, as shown in Figure 1, and which provided the data for this study.

The system enables to associate the weight of each vehicle transiting, or approaching, the A3 to its license plate, through a series of automatic number plate recognition (ANPR) cameras. This allows to identify and monitor each vehicle’s path and offers to possibility to requesting or enforce the rerouting of vehicles that do not comply with certain load-related criteria.

To provide some context, it should be mentioned that, in the aftermath of the collapse of the Polcevera bridge in Genova (Calvi et al., 2019), a set of Italian guidelines was released for the classification and management of risk, the assessment of safety and the monitoring of existing bridges, hereafter LL.GG.2020, (CS.LL.PP., 2020). The intention behind the LL.GG.2020 guidelines was to enable temporary transit on structurally substandard bridges by limiting maximum allowable vehicle weight on the basis of structural monitoring and safety verifications. In this context, the level of traffic restriction depends, not only on structural performance, but also on the level of traffic control imposed on the infrastructure of interest,
that is, on the actual capacity of the network operator to prevent the transit of unauthorized vehicles. The largest admissible vehicle mass, according to the Italian transportation code, is 44 t (tons). In other words, only vehicles weighing 440 kN or less can circulate freely, without a special authorization.

To enable continued use of aging infrastructure, albeit with restrictions if the structural verifications demand it, the LL.GG.2020 guidelines prescribe traffic control that prohibits the transit of all overload vehicles, which are to be rerouted. Therefore, it was in the interest of the former operator (Autostrade Meridionali S.p.A., now superseded by SIS S.p.A.) to design and enforce a traffic control system to: (i) monitor all vehicles in transit on the route; (ii) identify vehicles with a mass exceeding 40t; (iii) issue a timely warning to the drivers not to transit on the Cava de Tirreni-Salerno section; (iv) identify potential infractions of this traffic limitation and report the culprits to the police for immediate removal from the highway and administrative sanctions. This system has been in continuous operation since its installation in early 2021 (Migliorino et al., 2021).

The WIM devices (i.e., scales), that provide the data discussed in the following, consist of austenitic stainless-steel plates equipped with optical fiber sensors. As shown in the schematic representation of Figure 2, these plates are embedded in the road pavement, so that a staggered pair of them are dedicated to cover an entire lane’s width, thus being able to intercept one semi-axle each, for any vehicle that stays exclusively within that lane while passing from the control point. This enables not only the measurement of each axle’s load, but also inter-axle distance, as well as vehicle width. However, this also implies that measurements of vehicles that pass the control point astride two adjacent lanes must be flagged for possible inaccuracy of some of the aforementioned quantities. The weight measurements on the WIM scales have been certified for the dynamic load recorded to be within a ten percent tolerance of the corresponding static weight.

Figure 2. Illustrative description of the WIM system for measuring, among others, the weight of all vehicles passing from detection points.

The main feature of the WIM system is real-time data updating and prompt communication with the highway’s central access system, via programmable logic controller (PLC) devices, whenever one of the devices detects a vehicle whose weight exceeds the permitted threshold, as defined above.

3. DATA DESCRIPTION
Each of the sixteen devices comprising the WIM system, placed on various lanes of the A3 as described above, provides a data record for every vehicle transit detected. During the one-year operation, from Feb. 1st 2021 to Jan 31st 2022, about thirty-six million (36,359,127) records became available. The most relevant information provided in each record are: license plate number; date & time of measurement; measurement quality and possible error code; the vehicle’s total weight, length, and width; vehicle speed and acceleration; number of axles; axle loads and inter-axle distances.

Three types of record quality are contemplated, tagged for brevity as OK, NL, and NR. NR stands for erroneous records, which are excluded from the dataset and further analyses. OK and NL can be considered usable, therefore only those are retained for subsequent elaboration and analysis. In fact, the acronym NL indicates a measurement that is not valid for legal purposes (i.e., imposing a fine for an infarction), even
though it can be technically valid. An error code is associated to each NL-tagged data record, which is used to denote a traffic violation (e.g., speeding) or a warning of the WIM system for over-the-limit vehicle weight. NL-tagged records also include records based on partial information. This would be the case of vehicles that are not travelling exclusively within the confines of a single lane during the measurement, causing at least one axle to not pass over the WIM scale with both wheels. In this case, that axle’s load is estimated by duplicating the force measurement of the wheel that actually managed to activate the scale during transit.

A type of result that be filtered out are multiple counts of the same vehicle on the same trip. To this end, all transits of the same vehicle detected within forty-six minutes of one another on more than one scale between the Pontecagnano and Scafati interchanges, in both directions, are only considered once (that being the time needed to make a round-trip between the two interchanges at an average speed of 60 km/h). Additionally, vehicles whose license plate was not recognized by the WIM system are also excluded. At the end of the filtering operations described above, the resulting number of records providing the basis for further elaboration, presented in the next section, is about seventeen million.

According to the Italian transportation code, vehicles with a total weight of less than 75 kN are classified as light, between 75 kN and 260 kN as medium, between 260 kN and 440 kN as heavy and beyond 440 kN as exceptional vehicles. It should be highlighted that this last category actually comprises all vehicles who exceed the legal limit for free transit on the Italian highways, in terms of mass, thus requiring special authorization to do so.

4. DATA ANALYSIS AND EMPIRICAL DISTRIBUTIONS

Based on the data discussed in the previous section, the following empirical frequency distributions were obtained for the vehicles: (1) total weight, (2) weight given the number of axles, (3) maximum axle load given the number of axles, (4) heavy vehicles’ axle-group load for single, tandem and tridem axles (5) mean inter-axle distance given the number of axles.

Figure 3 shows the frequency distribution of gross vehicle weight, in histogram format. Seeing as the modal value collects more than 80% of the data, impairing the readability of bins that count only a few thousand of data points, the figure is equipped with a magnified view of the data corresponding to vehicles with a weight greater than 100 kN, light commercial vans, which is to be expected.

Further useful information can be extracted from the data by taking a closer look at the population of heavier vehicles. For this reason, the data are divided into four groups corresponding to the previously defined weight intervals of light (less than 75 kN), medium (75 to 260 kN), heavy (260 to 440 kN), and exceptional vehicles (above 440 kN).

![Figure 3. Empirical distribution of gross vehicle weight from one year of WIM data.](image)

Thus, Figure 4 shows the empirical distributions of vehicle weight within each of the four categories. Whilst light vehicles represent a 94% of the useable recorded data; with medium, heavy and exceptional comprising the remaining 4.2%, 1.3% and 0.5%, respectively, statistics of the three heavier categories can, in fact, be more influential for traffic-load related engineering applications.
This figure shows that vehicles within the 75 kN and 440 kN weight range follow a more uniform frequency distribution, unlike lighter vehicles where the distribution exhibits a distinct mode around 15 kN to 20 kN. On the other hand, the weight distribution of the exceptional vehicle category, starting at 440 kN, decreases sharply, reflecting the decreasing likelihood of increasingly massive objects being transported over the highway network, with the heaviest vehicle recorded tipping the scales at almost 1480 kN.

Another way to stratify the data, that has found application in the construction of bridge load models, is to examine the load transferred by axle groupings of heavier vehicles, such as trucks. In this sense, the recorded axle loads of all vehicles with a total weight in excess of 75 kN are divided into single axles, tandem axles and tridem axles, based on an inter-axle distance criterion whereupon axles less than 1.8 m distant from one another are considered as part of a group and their loads are summed (Lu et al., 2002). This operation is quite intuitive, as it can be expected that, given the total vehicle weight, the loads transferred through nearby axles are not independent. The marginal empirical distributions for the three axle groupings of all vehicles bar the light vehicle category, are provided in the histograms of Figure 5.
The figure shows that all three distributions exhibit one modal value at around 75 kN to 90 kN, but the tandem load distribution’s observed tail is far heavier than that of its single-axle counterpart, while the tridem axle load distribution is conspicuously bimodal. In fact, these two observations on the number and location of the (first) modal values, stemming from one year’s worth of traffic on the A3, are quite consistent with corresponding published distributions from WIM data recorded in France in the late eighties and mid-nineties (Calgaro, 1998; O’Connor et al., 1998). As a sidenote, it should also be mentioned that the traffic data that were recorded on the French A6 highway in the late eighties and referenced above, were very influential on the development of the EN-1991-2 traffic load model for road bridges.

On the other hand, a notable difference between the present dataset and these earlier data can be found in the maximum recorded values, with the maximum tridem axle load recorded among the recent Italian data being around 70 kN to 150 kN larger than those of the earlier datasets mentioned. This difference can be attributed to the recording duration, which was of the order of a few weeks for the datasets cited for comparison. This brings into the limelight the already mentioned issue of the disparity between desired return period of design load effects on bridges and typically available traffic monitoring time intervals: traffic composition differences aside, it is only to be expected that longer observation periods will result in larger maximum load values, as they are tantamount to sampling the (unknown) parent distribution of axle loads more times. For example, compare these with the fact that the Eurocodes consider one-thousand years for the return period of traffic-load effects to be considered in structural safety checks.

With this in mind, the one-year data considered here are also used to derive empirical distributions for the daily maximum load of an axle group, that is, distributions that are typically assigned parametric models in the literature (Flint & Jacob, 1996). These frequency distributions from three-hundred and sixty-five days, are shown in Figure 6.

5. FINAL REMARKS
This short article presents empirical distributions of traffic loads based on one year of WIM data from a traffic control system for a 52 km long highway in Italy connecting two important ports in southern Italy, Naples and Salerno. Data for the analyses, were continuously recorded from Feb. 1st 2021 to Jan. 31st 2022. After the data have been filtered for possibly unreliable information, a remaining sample of about seventeen million transits has been used to derive the empirical distributions of the vehicles’ main features. The focus was on parameters that are influential for the determination of structural actions on road bridges, such as axle loads. Apart from the marginal observed distributions of gross vehicle weight and axle loads, sets of conditional empirical distributions, given vehicle weight category or type of axle grouping, were also derived. Some distributions of the daily maxima were obtained as well. It was discussed that these...
distributions follow some general trends observed previously in other datasets from the literature. These distributions and the data used to derive them are made available for further studies and can be reached at a dedicated online repository https://doi.org/10.6084/m9.figshare.c.6347495.v1.

6. REFERENCES


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