Probabilistic Considerations and Use of WIM Data for Assessing Structural Safety Effects of Permitting 74-Ton Heavy Trucks on Norwegian Bridges

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ABSTRACT: The Norwegian Public Roads Administration has been asked to provide scientific background on the effect of increasing the maximum allowed traffic load to 74 tons on the structural safety of existing road bridges. This is a challenging task that requires careful attention to the way structural safety is assessed. With this paper, we want to highlight the aspects of importance when addressing this task and demonstrate the possibilities of utilising information from weigh-in-motion measurements. The background for the Norwegian traffic load model for the assessment of existing bridges is reviewed and probabilistic considerations that are important for evaluating the effect of increased traffic loading are identified. The relation between the legal load limit and the loading situations in different limit states is deliberated, with a focus on the ultimate limit state and extreme value prediction for long time horizons. One year of traffic weight data from a national Norwegian road is used for illustration purposes and the effect of different statistical considerations and assumptions is evaluated. It is indicated that the Norwegian traffic load model for assessment may be considerably less conservative than what can be justified from the measurements, and it is suggested to review the load model further with a probabilistic approach. When making decisions on legal load limits, a proper understanding of the impact these limits have on structural safety is crucial.

1. INTRODUCTION

In order to increase the efficiency of freight transport and reduce emissions, vehicles on the European road network are getting heavier. This is also the trend in Norway, where 74-ton heavy timber trucks are permitted to operate, as opposed to the regular 60-ton limit, in a pilot project in the region Innlandet. To accurately assess the effects of such a change in loading is of paramount importance to avoid unnecessary strengthening while keeping bridges safe. Weigh-in-motion (WIM) systems are simple techniques to measure the weight of vehicles in the traffic network. The data is easy to obtain, but actually making use of it requires careful consideration of the uncertainties associated with traffic loading.

One interesting attribute of the traffic load compared to other hazards is that it is typically regulated. With perfect regulation of traffic loads, it could be treated deterministically, but this would in practice require to weigh every truck before it is allowed to pass a bridge, which is not feasible other than in extreme situations. The traffic load model must therefore take into account the possibility of illegally overloaded vehicles.

The different types of limit states require different traffic models. For fatigue, a combination of the number of load cycles and the magnitude of the load contributes to the accumulated fatigue damage. Serviceability limit states cover situations of normal use that induce cracking, deflection or other usability issues, and require information about normal traffic. Ultimate limit states, on the other hand, are used to represent extreme situations with unlikely traffic events. This differentiation is important, as it has an impact on the domain of interest for traffic load modelling. Ultimate limit states require extrapolation of traffic loads to long return periods which magnifies all uncertainties immensely. The return period can be seen as a reference value chosen within a structural design code that together with the other chosen variables and partial factors result in sufficiently safe structures. In other words, the return period is not directly related to the safety level. With this in mind, it is less striking that the American code AASHTO specifies 75 year return period whereas the Eurocode uses 1000 years.

For design of new bridges, the Eurocode traffic load model is widely accepted. It consists of four notional load models representing typical traffic situations of tandem loads and uniformly distributed loads. The characteristic values in terms of axle loads Q_i and uniformly distributed loads q_i, where i is the lane, are defined as the 1000-year return value, or a load that will be exceeded with 5% probability during 50 years. The background work of the Eurocode traffic load model by Sedlacek et al. (2008) describes how the characteristic values were derived. Three weeks of weight data from Auxerre, France, collected in 1986 was considered. This data set was chosen because it had the highest traffic loads among the locations for which data was available. The upper tail of the measurement data was fitted to a normal distribution and extrapolated to a 1000-year return period. The European countries have the option to reduce the characteristic values with factors $\alpha_{Q,i}$ and $\alpha_{q,i}$ in their national annexes, to account for deviations in traffic characteristics such as traffic intensity. Norway reduces one factor $\alpha_{q,i}$ to 0.6 but keep the rest of the factors equal to 1.

The assessment situation is principally different from the design situation, and this has implications for the traffic load model. First, the time horizon may be different, as the bridge approaches the end of its service life. Second, information and uncertainties are different in the assessment situation. The traffic situation at the bridge to be assessed can deviate significantly from the traffic situation considered in the Eurocode model. One aspect is that the traffic may be regulated by law, and information about vehicles not complying with the law is therefore crucial. Last, it is more costly to increase the safety of an existing bridge than in the design stage, which suggests that the requirements for structural safety should be relaxed.

A traffic load model for assessment of existing structures should ideally be constructed at several levels of detail. Adjusted characteristic values valid for all typical assessment situations are needed. One clear and comprehensive way to introduce such reductions is to make use of the previously mentioned reduction factors $\alpha_{Q,i}$ and $\alpha_{q,i}$ in the Eurocode. Switzerland prescribes differentiated reduction factors α_i for assessment of bridges for different types of bridges and span lengths (Brühwiler et al., 2012) and a similar approach is proposed for Croatia (Skokandić et al., 2019). In addition to adjusted characteristic values, a probabilistic traffic load model for assessment is a valuable tool for cases when partial factor methods are not sufficient and a structural reliability analysis is needed. Last, there is a need for guidance on how to construct bridge-specific load models for the occasional cases with extraordinarily large uncertainties and high consequences. These three needs can be met by rational treatment of uncertainties and the use of WIM and B-WIM data. We claim that not only are these needs within reach for bridge owners but also that they will be crucial in adapting to resource-efficient maintenance of existing infrastructure.

The aim of this study is to provide bridge owners with a practical approach for constructing a load model for assessment of existing structures. Special attention is directed to what aspects WIM data can, and cannot, be utilised for. By differentiating uncertainties throughout the modelling chain, the data can be used to inform the model in an effective way. With this uncertainty framework and data, the assumptions behind the current load model for assessment in Norway are examined and improvements are suggested.

2. CURRENT PRACTICE

The Norwegian traffic load model for assessment of existing road bridges (NPRA, 2021) is based on the regulation for use of vehicles (FOR-1990-01-25-92, 1990) where the traffic is classified into normal and special vehicles, and details about permissible weights and axle configurations for vehicles are found. As an example, the road stretch from which the WIM data is taken is open for Bk10/74 and Sv12/100. Without a special permit, vehicles with axle weights of 10 tons and a total weight of 74 tons are allowed to drive. With a special permit, the limits are 12 and 100 tons. In addition, one-time permits can be issued for even heavier vehicles. To avoid having to deal with numerous types of vehicles, equivalent loads are established for every class to mimic the load effect of permissible vehicles. These are taken as characteristic loads. It should be noted, that this definition is considerably different from the Eurocode definition being the 1000-year return value. The partial factor has therefore to account for all uncertainties and should be calibrated to reach the desired safety level, e.g. described as a target reliability. No statement of the required safety level can be found in the Norwegian guidelines. Typically, the acceptable yearly reliability is in the range of 3.1-4.7 (corresponding to a yearly probability of failure of 10^{-3}-10^{-6}). It follows that we are interested in rare events that are per definition rarely observed.

3. RATIONAL TREATMENT OF UNCERTAINTIES

The uncertainties in traffic load modelling originate from several sources. It is tempting to combine all uncertainties and treat them with one safety factor, but with this approach conservative assumptions have to compensate for the lack of information and understanding, or we lose control over the structural safety. With more accurate treatment of specific uncertainties, it is possible to logically deduce the effect of new information.

In order to demonstrate how uncertainties in traffic load modelling for ultimate limit states can be treated more rationally, a flowchart is provided in Figure 1, differentiating some of the important variables. In this figure, we see that the only aspects treated explicitly in the current Norwegian load model are the legal weight and axle configurations and the combination of vehicles. The dynamic amplification factor and the uncertainties related to the load effect model are mentioned to be included in the characteristic values and safety factors. Treatment of the other uncertainties in Figure 1 is lacking. There are several ways to interpret this absence: Either the uncertainties have been treated appropriately in background work and are included implicitly in the guidelines, or either they have (intentionally or unintentionally) been ignored. Either way, this absence can be evaluated by setting up a traffic load model that includes detailed treatment of the aspects deviation from law, traffic intensity, reference period and extrapolation to extreme values, through analysis of WIM data. The aim is not to present a perfect load model, but to find a reasonable combination of solid theory and practical considerations that could provide support for the continued safe use of the current traffic load modelling guidelines. Different loading situations govern for bridges with different span lengths. Simply put, heavy axles are critical for short-span bridges, total vehicle weight for medium-span bridges and congestion situations for long-span bridges. In the remainder of the paper, we limit the discussion to modelling one heavy truck. This is a reasonable loading situation for bridges with spans in a similar order of magnitude as the length of a truck. In this way, combinations of vehicles can be neglected, and the message of the paper will appear more clear. Future traffic trends are also ignored.

The notional load model causes load effects throughout the bridge, in terms of stresses or section forces such as moment and shear, determined by an uncertain mechanical model. Influence line/area, girder distribution factor and dynamic amplification factor are concepts that are commonly adopted as parts of this model. By addressing the uncertainties of this model implicitly

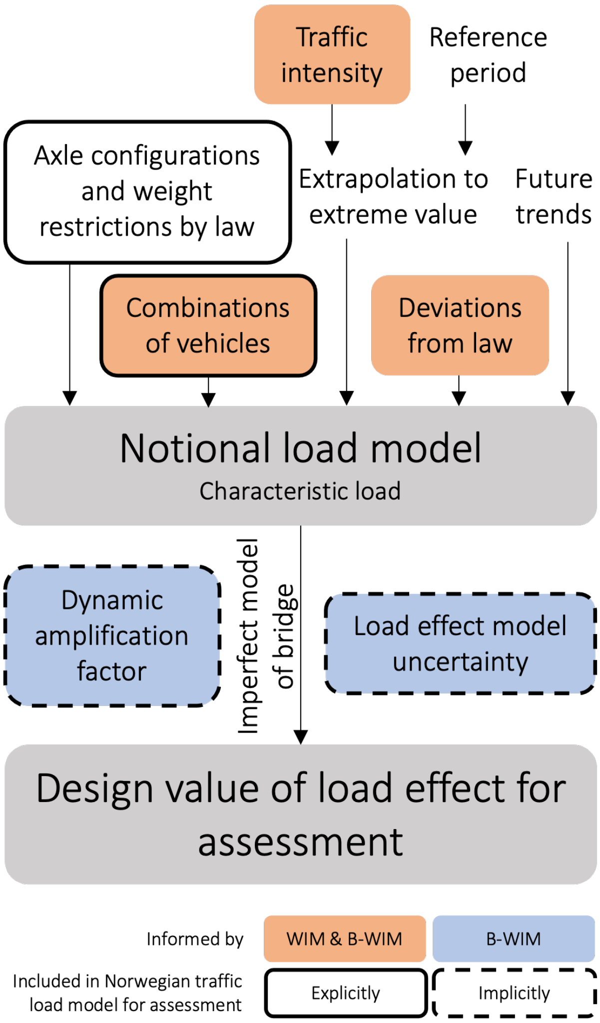

Figure 1: Differentiation of aspects for traffic load modelling with an indication of what aspects are included in the Norwegian traffic load model and what aspects can be informed by WIM and B-WIM data.

by applying a partial safety factor, the design value of the load effect for assessment is obtained. Alternatively, uncertainties can be dealt with explicitly in a structural reliability analysis.

4. USE OF WEIGH-IN-MOTION DATA

WIM systems measure axle weights and distances with sensors in the pavement or attached to a bridge. WIM data carries information about the notional load in form of the actual stream of vehicles passing the measurement location. Bridge-WIM data can, in addition, replace or complement the mechanical model. In a B-WIM system, the weight of passing vehicles is calculated from strains measured in the bridge. These strains, measured at smart locations, are exactly the load effects that are needed for assessment. In fact, the B-WIM system is a monitoring system. However, the main purpose of B-WIM is to obtain the same data as from WIM measurements, i.e. weights of the stream of vehicles. When selecting appropriate bridges for B-WIM, short single-span concrete bridges without curvature are preferred. These requirements are not necessarily fulfilled for the bridges in need of assessment.

WIM and B-WIM data are typically collected for time periods of weeks, months or possibly a few years. To make predictions of extreme values for reference periods of 50-1000 years, which can be required for assessment, extrapolation is needed. To summarise, there is a chain of models leading from the weight of individual vehicles to a design traffic load effect. WIM and B-WIM data can provide information to parts of this modelling chain, but the data cannot eliminate all uncertainties.

5. EXTREME VALUE MODELLING

The common approach to modelling extreme values is to assume that an event can be represented by an independent and identically distributed random variable. An extreme event can be extrapolated from this basic event by considering multiple occurrences by

$$F_n(x) = [F_1(x)]^n \tag{1}$$

where $F_1(x)$ is the basic event and n is the number of occurrences. The differentiation of independent events can be done by (time) block-maxima or peaks-over-threshold methods. If block-maxima is chosen, the shortest period that complies with the requirement on independence is one day for traffic loading, as the traffic is expected to follow some trend during one day. To avoid interference of possibly different traffic characteristics on weekends, business days are usually considered.

The generalised extreme value distribution $GEV(\xi,\mu,\sigma)$ has the cumulative distribution function

$$F(x) = \begin{cases} \exp\left(-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right), & \text{if } \xi \neq 0 \\ \exp\left(-\exp\left[-\frac{x-\mu}{\sigma}\right]\right), & \text{if } \xi = 0 \end{cases} \tag{2}$$

It is called general as it includes three types of distributions with different shape parameters affecting the thickness of the tail. The Weibull distribution with $\xi > 0$ has an asymptotic behaviour whereas the Gumbel distribution ($\xi = 0$) and Fréchet distribution ($\xi < 0$) approach infinity for very rare events. It is argued that traffic load is a physically bounded phenomenon and that the Weibull distribution is a reasonable choice. Gumbel distribution is also commonly used, as it is seen as a conservative choice. The generalised extreme value distribution is indeed flexible, but this has also disadvantages. With one extra parameter, there is one extra degree of freedom that the data can fit to. This mathematically better fit may conflict with the understanding of the underlying phenomena.

OBrien et al. (2015) present a review of methods for assessing traffic load effects where seven different methods for inference were performed on one academic example and one real case. Tail fitting and full distribution fitting were distinguished, and predictive likelihood and the Bayesian approach were said to be less accurate than the other methods. However, these were the only methods that used full distribution fitting. The fact that longer blocks in the block maxima method is actually a way to adjust the fitting further into the tail, was not addressed. The least square method was used to fit distributions to data in the tail. Maximum likelihood estimation was not investigated in that study.

In this study, maximum likelihood estimation is used to infer parameters for the distribution from data. The idea is to maximise the likelihood

$$L(\theta \mid x) = \prod_{i=1}^{n} f(x_i \mid \theta) \tag{3}$$

where $f(x_i \mid \theta)$ is the probability density function, x_i are the observations and θ are the parameters of the chosen distribution. In other words, the parameters are selected such that the likelihood of observing the data given the parameters, is largest compared to other possible parameters. For the generalised extreme value distribution with $\xi \neq 0$, the negative log-likelihood (negative as optimisation algorithms typically minimise by default, log to avoid multiplication of very small numbers) is

$$\log L = -n\log\sigma - \left(1-\frac{1}{\xi}\right)\sum_{i=1}^{n}\log x_i - \sum_{i=1}^{n} {x_i}^{1/\xi} \tag{4}$$

6. DEMONSTRATION

WIM data from the traffic control station Ånestad is collected by the road administration for the purpose of identifying vehicles exceeding weight restrictions. The system installed uses quartz piezoelectric technology and is supposed to have an accuracy of ±5%. One year of data, from 2021-10-01 to 2022-09-30 was available for analysis. Weekends and public holidays were excluded, resulting in 255 days, for which the maximum weight is plotted in Figure 2. The location is, by Norwegian standards, highly trafficked with average daily traffic of 12 200 vehicles, of which 16% are longer than 5.6 meters.

The location is part of the road network in which 74-ton heavy trucks are permitted to operate in a pilot project, and bridges along this road stretch are therefore classified as Bk10/74 (max axle weight/max total weight). As the 74-ton trucks have to register to participate and are subject to extra controls, this traffic situation cannot fully be compared with the possible future situation where 74-ton heavy trucks may be permitted by default instead of today's 60 ton. In addition to class Bk10/74, bridges are also permitted for a special transport class called Sv12/100, allowing 100-ton heavy trucks with a special permit. As it is not obvious from the data which vehicles have this special permit, the normal and special trucks cannot be

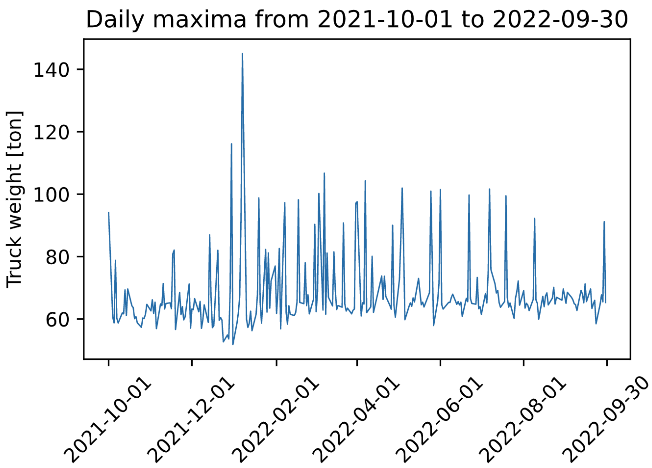

Figure 2: Time series of maximum truck weight on business days during one year.

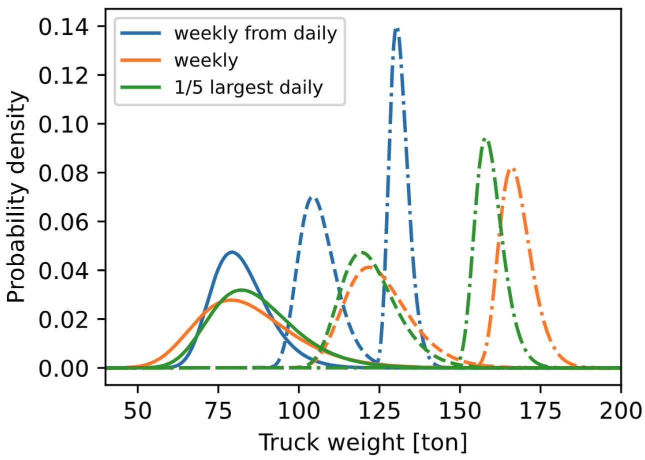

Figure 3: Probability density for weekly (solid), yearly (dashed) and 1000-year (dash-dotted) return periods.

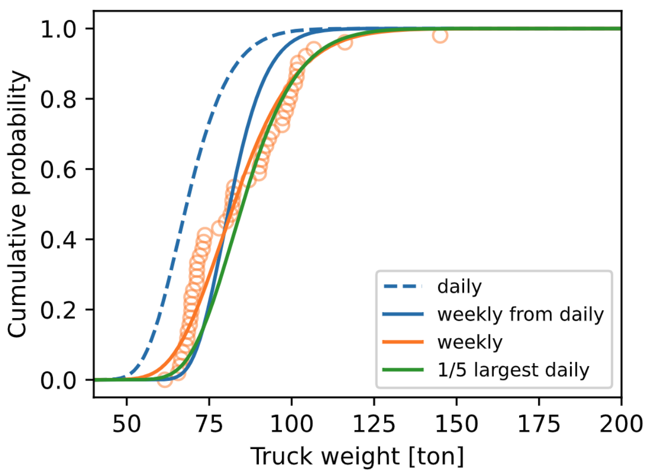

Figure 4: Cumulative distributions for daily and weekly maxima together with weekly maximum observations.

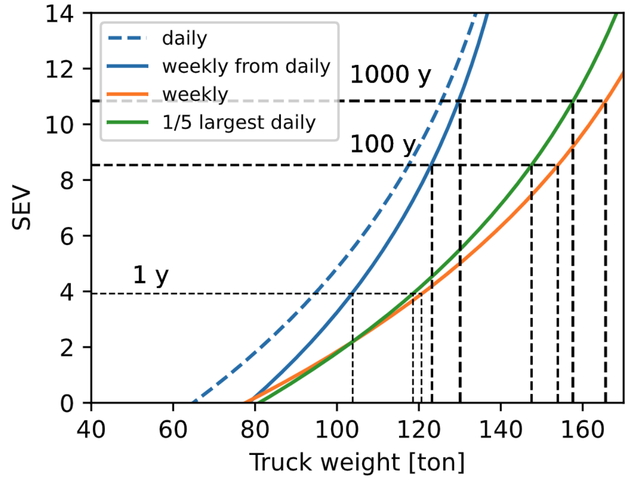

Figure 5: Extrapolation of distributions to 1, 100 and 1000-year return periods. The dashed line shows the daily maxima distribution that the weekly distribution (solid blue line) was extrapolated from. Note that the SEV has a different meaning for daily and weekly events.

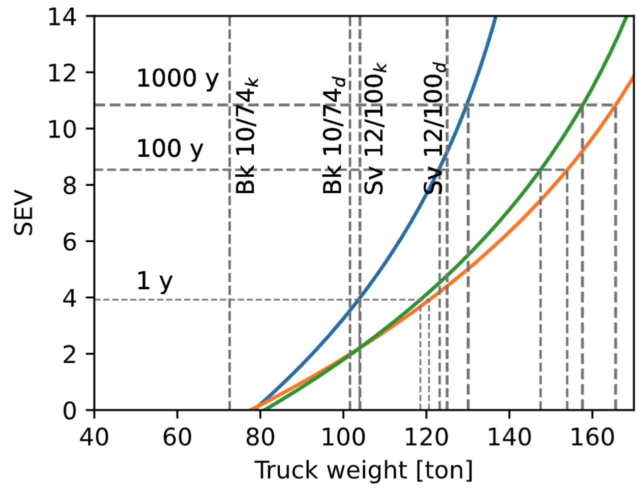

Figure 6: Comparison of the three extrapolated distributions and Norwegian characteristic and design loads (with subscripts k and d) for assessment in current regulations.

confidently separated. This is problematic as a 105-ton vehicle exceeding its permit on 100 tons is less exceptional than a 105-ton vehicle exceeding the 74-ton limit. It follows that it is difficult to relate the 74-ton limit to the measured data. However, an analysis of the mixed traffic can still provide valuable information on what traffic loads are expected in a certain period on a road open for Bk10/74 and Sv12/100 traffic.

Daily and weekly maxima were identified from the data set and fitted to Weibull distributions with shape parameter 0.1, which were extrapolated to one, 100 and 1000-year return periods. In addition, the largest 1/5 of the daily maxima were analysed, to demonstrate the effect of using more extreme data from the tail.

The probability density functions for the three considerations are shown in Figure 3. The expected value for one week return period is similar for the three models. They deviate slightly for one year and significantly for 1000 years. In Figure 4, the weekly cumulative distributions are plotted together with the data, showing that the distributions from weekly and the 1/5 largest daily maxima fit well to the upper tail of the data. The extrapolated distribution from daily maxima to one week seems to underestimate the truck weight. This means that there are different underlying traffic phenomena for different return periods, that are not captured by extrapolation. The discrepancy is magnified for longer return periods, see also Figure 5 for extrapolation shown on standard extreme variate scale (or Gumbel scale), where

$$SEV = -\log(-\log(F(x))) \tag{5}$$

Table 1 contains the parameters of the distributions. For the distributions fitted to data with maximum likelihood, the standard errors for the parameters are also given. The standard errors indicate that the statistical uncertainty is small, i.e. there are enough data points to create a distribution with confidence. However, the standard error is not a measure of the adequacy of the fitted distribution to the data or, more importantly, to the true population of heavy vehicles. If longer time blocks are chosen such as months or years, the number of data points would be fewer and the statistical uncertainty is expected to be larger.

According to Figure 6, the characteristic load $\mathrm{Bk}10/74_k$ specified by the Norwegian road administration is a load that is exceeded more often than once a week at the measurement location. For $\mathrm{Sv}12/100_k$, the characteristic load is exceeded on average every year or more often. As described earlier, in current Norwegian guidelines the definition of the characteristic value is the legal load. If extrapolation is assumed to be accounted for in the partial factors, a comparison to the design loads may be more relevant. Then, the return period is less than one year for $\mathrm{Bk}10/74_d$ and 1-100 years for $\mathrm{Sv}12/100_d$. Deriving the characteristic load as defined by Eurocode from the observed weekly maxima, results in 165 tons. This is 59% respectively 127% larger than the assigned values for $\mathrm{Bk}10/74_k$ and $\mathrm{Sv}12/100_k$. This suggests that the assigned values in the Norwegian traffic load model for the assessment of existing bridges may be too low to ensure safety. It could also be that the data set contains many heavy vehicles with one-time permits, which should have been excluded from the analysis. In any case, the characteristic load definition does not hold for ultimate limit state assessment, as it is clearly defined as a load that will be frequently exceeded.

Based on the observed data, a representation of the weight of one heavy truck to use for ultimate limit state assessment of nearby bridges for one year reference period can be roughly suggested. For probabilistic assessment, a Weibull distribution with parameters $\xi, \mu, \sigma = (0.1, 120, 10)$ could be reasonable and for assessment with partial factors, 120 tons could be taken as a characteristic value. However, such values should be prescribed as part of a calibration of the overall safety format to ensure an adequate and consistent level of safety.

7. CONCLUSIONS

Looking back at Figure 1, the current Norwegian load model only takes into account combinations of legal vehicles. With this study, we include deviations from the law by analysing real traffic data, and extrapolation to extreme values. The primary aspects left to assess to arrive at a complete load

Table 1: Parameters for distributions estimated with maximum likelihood (with standard error in parenthesis) and for extrapolated distributions.

	ξ	μ (SE)	σ (SE)
1 day			
daily	0.100	64.87 (0.578)	9.17 (0.315)
1 week			
daily	0.101	78.42	7.80
weekly	0.100	77.65 (1.92)	13.29 (1.37)
1/5 daily	0.100	80.98 (1.61)	11.59 (1.13)
1 year			
daily	0.101	103.79	5.26
weekly	0.102	120.80	8.97
1/5 daily	0.101	118.58	7.82
1000 year			
daily	0.101	130.06	2.64
weekly	0.101	165.55	4.50
1/5 daily	0.101	157.60	3.92

model are future trends, the dynamic amplification factor and load effect model uncertainty. In addition, the traffic load model must be integrated into the safety format, for which requirements on safety can be evaluated.

From the probabilistic analysis of WIM-data, we conclude the following:

- Extrapolation of weekly and largest 1/5 daily maxima results in similar return values, whereas extrapolation of all daily maxima seems to underestimate the extreme traffic loads
- To be able to distinguish the illegal heavy vehicles from the legal ones in a data set is important for utilising the data for traffic load modelling
- A probabilistic load model based on one year traffic data was proposed for representation of one heavy truck on the national road stretch close to Ånestad
- Analysis of data from other locations are needed to validate the load model for use on other national roads

In the context of the overall safety format, the following remarks are made:

- The increase of the legal limit from 60 to 74 ton has little impact on the ultimate limit state assessment for short and medium span bridges that are permitted for special transport, given the current safety format
- However, a more thorough evaluation of all effects of this legal increase is needed, including possible violations of the safety format itself
- In fact, the current traffic load model for assessment prescribed by the Norwegian road administration may not be acceptable for use in ultimate limit state assessment
- Differentiation of uncertainties related to traffic load modelling is required to enable accurate reduction of uncertainties by the use of new information
- We suggest the Norwegian road administration to calibrate the traffic load model based on weight data to a specified target reliability for existing structures with careful consideration of the different uncertainties

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