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Autor: Bailey, Simon F.

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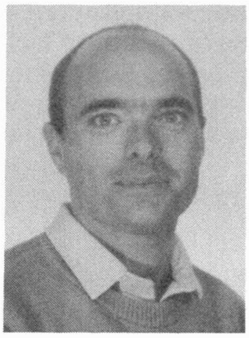
Traffic Action Effect Reduction Factors for Bridge Evaluation

Simon F. BAILEY
Research Engineer
ICOM-Steel Structures, EPFL
Lausanne, Switzerland



Simon Bailey, born in 1963, graduated from Southampton University, UK, in 1984 and joined a firm of consulting engineers where he worked on the design, construction, and maintenance of structures. Since 1990 he has been conducting research into bridge evaluation at ICOM where he obtained his doctoral degree in 1996.

Summary

This paper presents a simple method for modifying the Swiss design traffic load model in order to take account of the difference between "design traffic" and the actual traffic which uses a given road bridge. This method can be used for the evaluation of structural safety and involves the use of a reduction factor derived as a function of six traffic characteristics which are calculated from site measurements. The paper also describes the development of the method and presents an example of its application.

1. Introduction

1.1 Background

Road-traffic design load models are inherently conservative because of the high uncertainty about traffic loads at the design stage. Furthermore, models must be valid for structures of all types and spans. The increased cost of construction due to the use of a conservative design load model is small and necessary to allow for uncertainty and to simplify the design process. However, once a structure is in service, the cost of an over-conservative evaluation could be much greater, and thus justifies the consideration of actual traffic and the effects it produces. There are thus two important differences between bridge design and evaluation, that is before and after a structure is in service :

design : high uncertainty

evaluation : high cost of increasing safety

Considering actual traffic during bridge evaluation can reveal the extent to which a bridge may have been over-designed through using a conservative traffic load model. In this way, maintenance needs within a bridge stock can be ranked more accurately and unnecessary strengthening or traffic restriction might be avoided.

The main aim of research recently completed at ICOM was therefore to develop a simple method for the consideration of site specific traffic loads as a function of parameters describing the bridge and traffic, referred to as site characteristics. This method is based on a site specific probabilistic model of traffic action effects derived from the results of computer simulations of traffic effects. The simulation program was used to generate random traffic actions for defined traffic conditions and the frequency distribution of maximum static effects was subsequently determined. The results of more than 1600 simulations were then used to derive empirical relationships between site characteristics and the parameters of a type III extreme value distribution of maximum effects. This paper explains how this probabilistic model has been used in order to develop a simple method for considering site specific traffic actions. This simple method is based on the application of reduction factors to action effects calculated using the Swiss design traffic load model. The paper is a summary of part of a doctoral thesis [1] and describes the innovative approach which was adopted for calibrating reduction factors using probabilistic methods considering various failure modes of bridge structures.

1.2 Considering actual traffic for bridge evaluation

The research described in detail in [1] has led to the development of two methods for considering actual traffic for bridge evaluation ;

- a site specific model of the frequency distribution of extreme traffic action effects,
- a simple method for modifying the effects of the design load model as a function of parameters describing the bridge and traffic, referred to as site characteristics.

The site specific model of the frequency distribution of extreme traffic action effects could be used in bridge reliability analyses for the evaluation of structural safety. However, practising engineers are rarely familiar with probabilistic methods and a simple method for considering actual traffic was therefore developed. This simple method is based on the application of a reduction factor to effects calculated using the Swiss design traffic load model. A reduction factor, α_Q, can be determined as a function of six traffic characteristics, and then applied to the traffic action effects in the following general expression :

$$S_d = S(\gamma_G \cdot G_m) + \frac{S(\gamma_Q \cdot Q_r)}{\alpha_Q} \leq \frac{R}{\gamma_R} \tag{1}$$

The use of the simple method in practice requires some knowledge of the traffic using the bridge which is being evaluated. Traffic data can be collected using weigh-in-motion techniques [2]. Data has to be analysed in order to calculate the mean, standard deviation and maximum value of heavy-vehicle linear-weights allowing for dispersion due to errors in the measurement systems.

1.3 Development

The site specific model of the frequency distribution of extreme traffic action effects was developed as the first stage of the research. This model was subsequently used in a second stage which consisted of calibrating reduction factors for the simple method. The site specific model of the frequency distribution of extreme traffic action effects has been based on the results of a traffic simulation program. The simulation program generates random traffic loads for defined traffic conditions and determines the frequency distribution of maximum static effects, as described in [1].

In the second stage of research, the site specific model of the frequency distribution of extreme traffic action effects was used in reliability analyses to calibrate reduction factors for the simple method for considering site specific traffic actions. Reduction factors were calibrated for different types of hypothetical traffic, bridge and action effect, as described in Section 2.2. A parametric study then enabled the identification of relationships between reduction factor and site characteristics. The simple method incorporates the relationships for the six most important traffic characteristics.

2. Traffic action effect reduction factors

2.1 Bridge evaluation with partial load factors and reduction factors

The evaluation of existing bridges will not usually be based on reliability analyses since practising engineers are not familiar with probabilistic methods. The site specific model of the frequency distribution of traffic action effects presented in [1] will only rarely be used during bridge evaluation. However, practising engineers are familiar with the partial factor approach to bridge design, and thus this is the most suitable format for bridge evaluation. There is therefore a need to introduce the concept of a site specific traffic load model into the partial factor approach to the assessment of structural safety. It was therefore decided to base the consideration of actual traffic on the Swiss design traffic load model and to propose reduction factors to be applied to it as a function of site characteristics. This reduction factor thus represents the difference between the design traffic which the design load model represents and the actual traffic which uses a given road bridge. Verification criteria would thus have the form of Equation (1). This section presents the calibration of these reduction factors using probabilistic methods and the simple method which was developed for deriving reduction factors as a function of site characteristics.

2.2 Calibration of reduction factors

Reduction factors were calibrated by comparing the frequency distribution of maximum effects due to a hypothetical traffic to that of the design traffic. The Swiss design traffic load model was developed using probabilistic methods and the type of traffic that it represents is thus known [3]. For a given action effect (support moment, midspan moment or support shear) and a defined bridge (span, construction type), the frequency distributions of maximum traffic action effects were derived using the site specific model developed in [1] for both the design traffic and a hypothetical actual traffic. Calibration then consisted of finding a reduction factor, α_Q, such that the frequency distribution of design traffic effects divided by α_Q was "equivalent" to the frequency distribution of hypothetical actual traffic effects, as shown in Figure 1. This figure illustrates the probabilistic approach, considering traffic actions and live load carrying capacity, which was used to determine the "equivalence" of frequency distributions. The figure shows that rather than simply considering a statistical characteristic of the traffic action effect frequency distributions, "equivalence" is defined as equal reliability. Reliability was estimated using the FOSM method by considering the frequency distribution of live load carrying capacity of the hypothetical bridge in a limit state function appropriate to the type of bridge and action effect being considered. This approach is explained in more detail in [1].

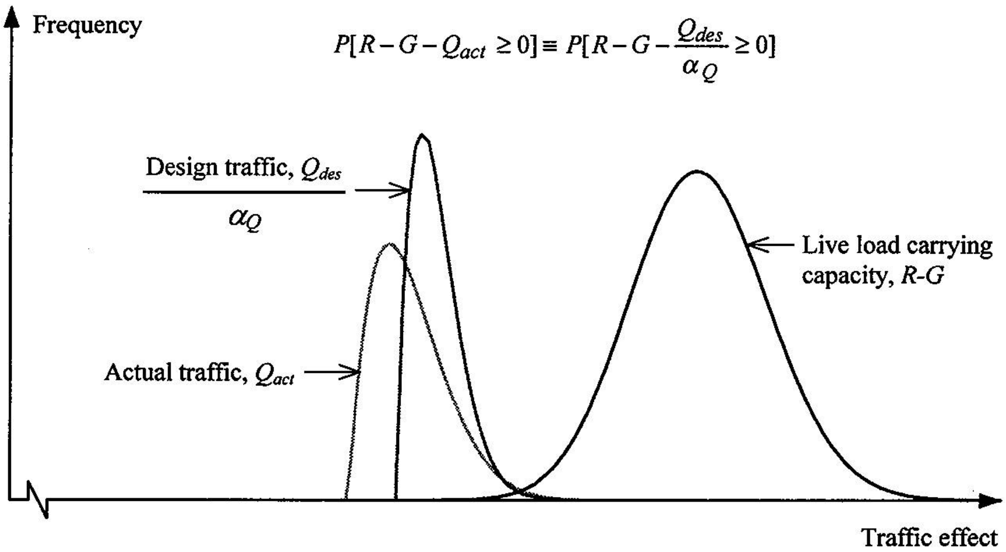


Fig. 1 Calibration of traffic action effect reduction factors

The calibration procedure was repeated for different types of traffic, bridge and action effect in order to enable a parametric study of the relationships between reduction factor and site characteristics. Figure 2 presents an example of the results of the calibrations, and shows the variation of reduction factor, α_Q, as a function of the mean value of heavy-vehicle linear-weight, μ_q, with all other traffic characteristics equal to those of the design traffic. The results for two lanes of traffic on many different types of composite bridge and action effect are shown. One bound is defined by the relationship for the support moment in a continuous box-section bridge with spans of 50, 70 and 50 m. The second bound is defined by the relationship for the midspan moment in a continuous slab-on-beam bridge with spans of 22, 30 and 22 m. The figure shows an inverse relationship, with the reduction factor increasing as the mean value of heavy-vehicle linear-weight decreases. The reduction factor is equal to 1.0 when μ_q is equal to the 'design' value of 14.5 kN/m.

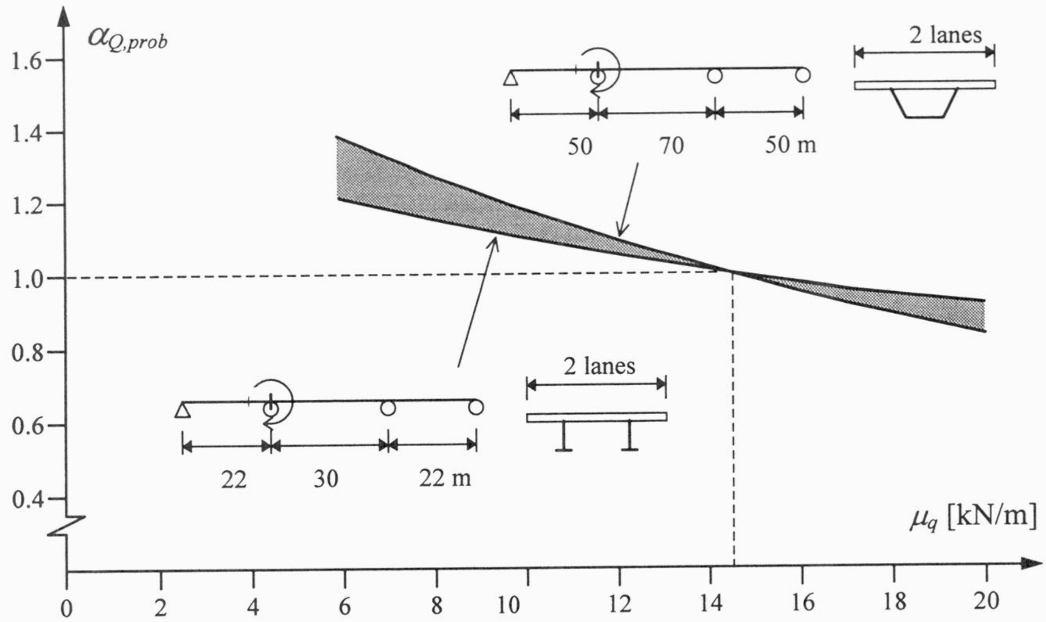


***Fig. 2** Variation of reduction factor as a function of the mean value of heavy-vehicle linear-weight*

The combined and individual influences of 13 different site characteristics were considered in the parametric study. Quantitative relationships between individual parameters and traffic action effect reduction factor were established and the most important characteristics were identified. The next section presents the simple method for determining reduction factors which was developed using these relationships.

2.3 Simple method for determining traffic action effect reduction factors

The individual influences of site characteristics are not independent and it is therefore not possible to consider the combined influence of all traffic characteristics by simply multiplying the appropriate individual reduction factors. However, on the basis of the individual influences it was determined that only the following traffic characteristics need to be considered in a simple method :

- maximum value of heavy-vehicle linear-weight, $q_{\max}$
- mean value of heavy-vehicle linear-weight, μ_q
- standard deviation of heavy-vehicle linear-weight, σ_q
- proportion of heavy-vehicles in the traffic, HV
- volume of traffic, N
- percentage of free-moving traffic, F

A relationship involving these six traffic characteristics was developed by a combination of trial and error and least squares fitting in order to obtain the best agreement with the calibrated reduction factors. It was found that the simple multiplication of individual reduction factors produced errors which increased as traffic characteristics diverged further from the design traffic values. Setting limits on the validity of the relationship and dividing the product of individual factors by the average factor was found to be the most efficient way of ensuring that, in the majority of cases, inaccuracy lead to the under-estimation of a reduction factor.

The following six expressions were derived to model the influence of the most important traffic characteristics (range of validity shown in brackets) :

$$c_1 = \frac{q_{\max}}{73} \cdot 0.2 + 0.8 \qquad (40 \le q_{\max} \le 80) \tag{2}$$

$$c_2 = \frac{1}{\frac{\mu_q}{14.5} \cdot 0.65 + 0.35} \qquad (6 \le \mu_q \le 20) \tag{3}$$

$$c_3 = \frac{1}{\frac{\sigma_q}{6.0} \cdot 0.6 + 0.4} \qquad (2 \le \sigma_q \le 8) \tag{4}$$

$$c_4 = \frac{1}{\frac{HV}{0.25} \cdot 0.7 + 0.3} \qquad (0.1 \le HV \le 0.4) \tag{5}$$

$$c_5 = \frac{1}{\log(N) \cdot 0.08 + 0.33} \qquad (10^5 \le N \le 10^9) \tag{6}$$

$$c_6 = \frac{F}{94} \cdot 0.2 + 0.8 \qquad (40 \le F \le 100) \tag{7}$$

The coefficients calculated using Equations (2) to (7) are then combined using the following expression in order to determine the appropriate traffic action effect reduction factor :

$$\alpha_Q = \frac{c_1 \cdot c_2 \cdot c_3 \cdot c_4 \cdot c_5 \cdot c_6}{(c_1 + c_2 + c_3 + c_4 + c_5 + c_6)/6} \tag{8}$$

Using this simplified method, 95% of the reduction factors, α_Q, are conservative and the remaining 5% do not over-estimate $\alpha_{Q,prob}$ by more than 5%, as illustrated in Figure 3.

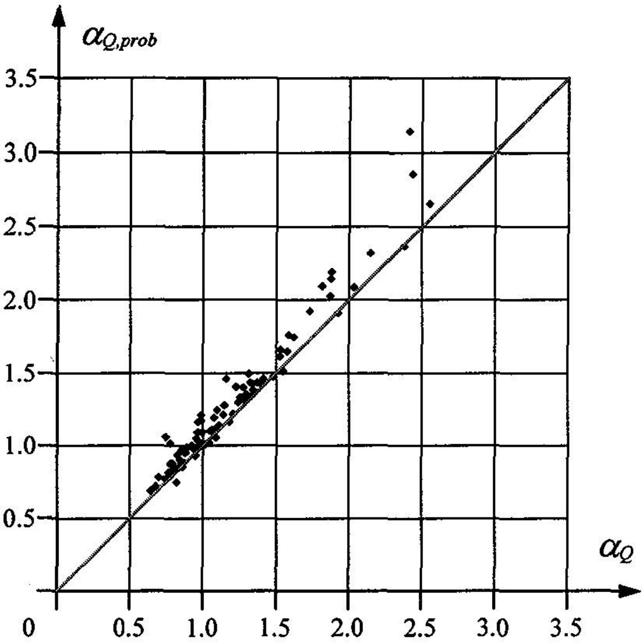


Fig. 3 Comparison of traffic action effect reduction factors derived using the probabilistic approach, $\alpha_{Q,prob}$, and the simple method, α_Q.

3. Example application of traffic action effect reduction factor

This section presents an example of the derivation of a reduction factor for application to the traffic action effects calculated with the Swiss design load model. The traffic action reduction factor is derived by combining of factors calculated for each of the six traffic characteristics presented in Section 2.3. The first step in using vehicle survey data is thus to determine these traffic characteristics. The maximum value of heavy-vehicle linear-weight should be obtained by fitting a beta distribution to measured data using standard statistical techniques (method of moments, for example). The mean and standard deviation of heavy-vehicle linear-weight should be calculated from data by taking into consideration any bias or dispersion associated with the measurement system. Traffic flow, volume and the proportion of heavy-vehicles are determined from measured vehicle speeds, vehicle counts and classification. The determination of traffic characteristics is illustrated for vehicle survey data collected at the Porte-du-Scex in Switzerland [1]. A histogram of measured heavy-vehicle linear-weights is shown in Figure 4.

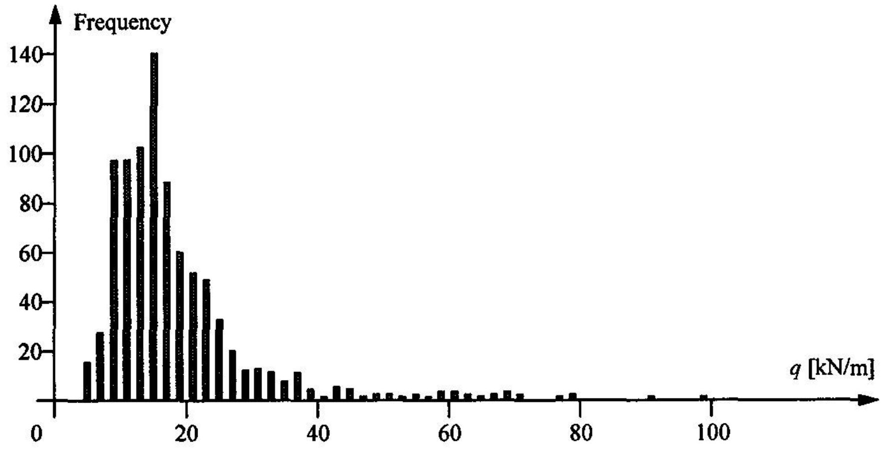


Fig. 4 Histogram of measured heavy-vehicle linear-weight, q

During calibration of the WIMstrip at the Porte-du-Scex site, the system was set up such that there was no bias between measured and actual weights. However, due to the vibration of vehicles as they pass over the WIMstrip as well as other sources of dispersion (only one wheel on each axle is weighed) a measurement error (real linear-weight / measured linear-weight) was noted with a coefficient of variation equal to 0.16. This variation is taken into account when calculating the mean and standard deviation of heavy-vehicle linear-weight, q :

$$\mu_q = \frac{\sum q_{measured}}{n} \tag{9}$$

$$\sigma_q = \sqrt{\frac{\sum q^2_{measured}}{\left(1+0.16^2\right)\cdot n} - \mu_q^2} \tag{10}$$

Equations (9) and (10) are only valid because there was no bias to the measurement error. The maximum value of heavy-vehicle linear-weight can be fixed by fitting a beta distribution with a lower bound of 4 kN/m to the measured data considering its first three moments adjusted to allow for a measurement error with the known coefficient of variation.

The values which were determined in this case are given in Table 15. Although traffic at this site was legally restricted to vehicles of less than 16 tonnes, the mean and standard deviation of heavy-vehicle linear-weight are not much lower than that measured on a Swiss highway at Göschenen [4]. However, the proportion of heavy vehicles in the traffic, *HV*, is very low due to the weight restriction which is imposed.

Traffic characteristic	**Notation**	**Value**	**Comment**
Maximum value of heavy-vehicle linear-weight	q_{max}	70 kN/m	
Mean value of heavy-vehicle linear-weight	μ_q	14 kN/m	
Standard deviation of heavy-vehicle linear-weight	σ_q	6 kN/m	
Traffic flow conditions	A	1 %	at-rest
	C	2 %	40 km/h
	F	97 %	500 veh/h
Traffic volume	N	20 million	10 years
Proportion of heavy-vehicles	HV	0.05	rounded up to 0.1

Table 1 *Traffic characteristics for calculation examples*

Six coefficients are calculated with Equations (2) to (7) using the traffic characteristics given in Table 1. The proportion of heavy vehicles, *HV*, is rounded up to 0.1, since the simplified method is not valid if *HV* is less than 0.1. Rounding up the value of *HV* will lead to a conservative value for the reduction factor.

$$c_1 = \frac{q_{max}}{73}\cdot 0.2 + 0.8 = \frac{70}{73}\cdot 0.2 + 0.8 = 0.99 \tag{2}$$

$$c_2 = \frac{1}{\frac{\mu_q}{14.5}\cdot 0.65 + 0.35} = \frac{1}{\frac{14}{14.5}\cdot 0.65 + 0.35} = 1.02 \tag{3}$$

$$c_3 = \frac{1}{\frac{\sigma_q}{6.0} \cdot 0.6 + 0.4} = \frac{1}{\frac{6.0}{6.0} \cdot 0.6 + 0.4} = 1.0 \quad (4)$$

$$c_4 = \frac{1}{\frac{HV}{0.25} \cdot 0.7 + 0.3} = \frac{1}{\frac{0.10}{0.25} \cdot 0.7 + 0.3} = 1.72 \quad (5)$$

$$c_5 = \frac{1}{\log(N) \cdot 0.08 + 0.33} = \frac{1}{\log(20 \cdot 10^6) \cdot 0.08 + 0.33} = 1.09 \quad (6)$$

$$c_6 = \frac{F}{94} \cdot 0.2 + 0.8 = \frac{97}{94} \cdot 0.2 + 0.8 = 1.01 \quad (7)$$

and then ;

$$\begin{aligned} \alpha_Q &= \frac{c_1 \cdot c_2 \cdot c_3 \cdot c_4 \cdot c_5 \cdot c_6}{(c_1 + c_2 + c_3 + c_4 + c_5 + c_6)/6} \\ &= \frac{0.99 \cdot 1.02 \cdot 1.0 \cdot 1.72 \cdot 1.09 \cdot 1.01}{(0.99 + 1.02 + 1.0 + 1.72 + 1.09 + 1.01)/6} = \frac{1.91}{1.14} = 1.68 \end{aligned} \quad (8)$$

This example illustrates that the determination of traffic action effect reduction factors is simple and that in certain cases a significant reduction is determined. The frequency distribution of heavy-vehicle linear-weight at the Porte-du-Scex is very similar to that of the Swiss 'design' traffic. For this reason the first three coefficients are close to 1.0. Similarly, the proportion of free-moving traffic is close to the 'design' value, and therefore has little influence on α_Q. In this case, the reduction factor of 1.68 is largely due to the low proportion of heavy-vehicles in the traffic.

4. Conclusions

Site measurements can be made during bridge evaluation in order to reduce the uncertainty about loads and resistance. In particular, the consideration of actual traffic and the effects it produces in a road bridge enables a more accurate assessment and a better ranking of maintenance needs.

A simple method for modifying the effects of the Swiss design load model as a function of traffic characteristics has been developed. This method involves the application of reduction factors to traffic action effects calculated with the design load model. It is applicable to verifications of structural safety based on longitudinal shear and moment effects determined by the simultaneous presence of at least two heavy-vehicles. Traffic action effect reduction factors are determined as a function of site characteristics using the equations presented in Section 2.3. The determination of reduction factors using these equations requires knowledge of the following six traffic characteristics:

- maximum value of heavy-vehicle linear-weight
- mean value of heavy-vehicle linear-weight
- standard deviation of heavy-vehicle linear-weight
- traffic volume
- proportion of heavy vehicles in the traffic
- percentage of free-moving traffic.

The simple method for considering actual traffic can be easily applied in practice with traffic data gathered using Weigh-in-motion techniques. The use of a site specific traffic load model rather than a design load model means that unnecessary repairs or traffic restriction can be avoided, leading to a better allocation of resources and an optimal use of the maintenance budget.

Acknowledgements

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Notation

α_Q	traffic action effect reduction factor
F	percentage of free-moving traffic
γ	partial factor (indices G, Q and R for permanent loads, traffic loads and resistance respectively)
G_m	average value of permanent actions
HV	proportion of heavy-vehicles in the traffic
μ_q	mean value of heavy-vehicle linear-weight
N	volume of traffic
$q_{\max}$	maximum value of heavy-vehicle linear-weight
Q_r	representative value of traffic actions
R	resistance
$S(..)$	effect of actions
S_d	design load effect
σ_q	standard deviation of heavy-vehicle linear-weight

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