Evolution of load conditions in the Norwegian railway network and imprecision of historic railway load data

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ABSTRACT

This paper describes historic load conditions in the Norwegian railway network to improve estimates of the remaining service life of bridges. Data on rolling stock, traffic and infrastructure throughout the history of the railway are presented. Axle loads, geometry, design, composition and operation of both passenger and freight trains have changed several times since the initial construction. The capacities of both rolling stock and infrastructure influence the load conditions in a railway network. Historic loads may have been more severe than modern loads for certain structural details. A probability distribution of load variables for a specific bridge cannot be obtained in the general case. Future research directions and suggestions for the use of non-probabilistic data in estimating the service life of bridges are discussed.

KEYWORDS

Bridge loads; service life; railway bridges; rolling stock; locomotives; imprecise data

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1. Introduction

Technological advances and population and trade growth have led to increasing axle loads and train speeds, placing higher demands on the ageing railway infrastructure. The existing infrastructure must be assessed under conditions of increased operational demands to ensure safe operation of the transportation system. To this end, numerical models are essential due to the vast number of components requiring assessment. Numerical models are used to determine the appropriate actions and predict the condition of many parts of the infrastructure, e.g., bridges (Imam, Chryssanthopoulos, & Frangopol, 2012; Imam & Righiniotis, 2010; Imam, Righiniotis, & Chryssanthopoulos, 2007). The importance of load conditions at the site is common to all such assessment tasks.

Bridges are structures with very long service lives and represent essential infrastructure components. A large portion of Europe's oldest bridges are made of steel (Sustainable Bridges, 2007). Fatigue is one of the primary damage mechanisms in steel bridges, and crack initiation, as well as crack growth, is governed by the load history at the site.

In the absence of data on historic loading conditions at a bridge site, the current train loadings and traffic intensity are commonly applied to the entire history of the structure in service life estimation. Hayward (2011, 2014) presents train loads on bridges in the British rail network throughout its history and shows that both axle weights and train speeds evolved tremendously from the first railways to today's modern railways. As the fatigue damage mechanism is highly sensitive to the magnitude of the stress range, assuming today's traffic over the history of the structure will yield grossly conservative results (Imam, Righiniotis, & Chryssanthopoulos, 2008). Ignoring historic loads can, on the other hand, overestimate the remaining service life, as such loads may have contributed significantly to the fatigue damage of certain details, as shown by Pipinato, Pellegrino, and Modena (2012b) and more recently by Imam and Salter (2017).

A better understanding of the historic loading conditions of the railway infrastructure will improve an evaluation of the existing infrastructure and facilitate a better allocation of limited resources to maintenance and renewal, therefore being essential to achieving both economic management of the infrastructure and an environmentally sustainable society.

Several authors have previously proposed load models for service life estimation of railway bridges due to fatigue damage. Åkesson (1994) suggests a simple load model, considering an *equivalent freight train*. It is assumed to have axle loads equivalent to the current maximum axle load during the entire history of the bridge.

The use of an equivalent freight train is also suggested in Sustainable Bridges (2007), in which the concept is extended to include the evolution of axle loads and allow for variations in train composition and wagon geometry. Details of past changes of axle loads and geometry are lacking; additionally, no recommendations regarding the selection of locomotive and wagon geometry, train type, train composition or traffic intensity are provided. Pipinato and Modena (2010) adapt the model but, similarly, do not present any further details of the historic fatigue load model.

Imam, Righiniotis, Chryssanthopoulos, and Bell (2006) present a model of historic load conditions of British railways. The model divides the railway history into two periods, 1900-1970 and 1970-present. For the period from 1970 to the present, the fatigue for trains of medium traffic type defined in BS5400-10 (British Standards Institution, 1980) is used. The load model prior to 1970 is divided further into three sub-periods, each defined by three different trains, i.e., freight, passenger and local suburban trains. Each train has a particular locomotive with various geometries and axle loads; the passenger and freight wagons vary in axle loads, while the wagon geometry is unchanged throughout the entire period 1900–1970. The load model is extended in Imam and Salter (2017) to lines with only passenger trains or only freight trains, with the study also including a description of geometry ranges of locomotives, freight wagons and passenger wagons of the rolling stock prior to 1970.

Although Imam and Salter (2017) present certain data on the ranges of values of the rolling stock geometry, the current literature lacks a concise overview of the variations and ranges of variables defining the train loads. Specifically, data are needed on the ranges of possible axle load magnitudes and geometry of locomotives, freight wagons and passenger wagons, as well as on the composition and operation of trains, e.g., the number and type of wagons and locomotive speeds applicable to a train. Without such data, it is not possible to assess the uncertainty associated with service life estimates or identify parameters that the service life estimate is most sensitive to.

This paper makes two major contributions to the theory of service life estimation of railway bridges. First, it presents data for the loads, design and geometry of rolling stock, as well as available data relevant to the composition of trains throughout the railway's history to further assess the uncertainty associated with service life estimates. A foreign reader can adapt and extend the presented data to other countries' railways. Second, this paper provides a general discussion of the nature of available load data for specific bridges in the network. In general, the probability distribution of all load variables cannot be determined. The implications of this insight for the current practice are discussed, and future research directions are provided.

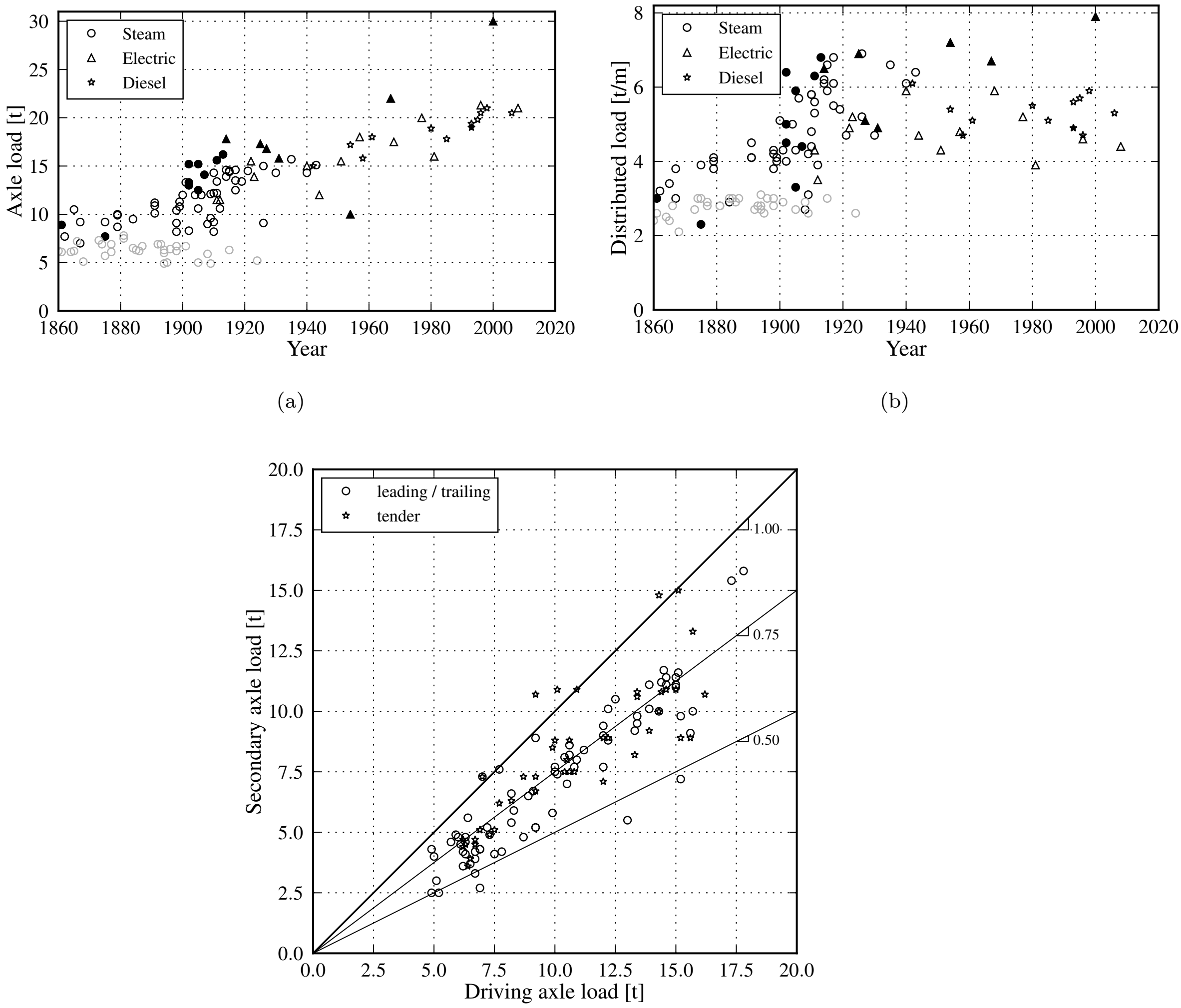
This paper is organised as follows. Section 2 and section 3 present data on the evolution of the axle loads, geometry and design of rolling stock available to the railway network throughout the railways' history. Section 4 considers the composition and operation of trains. Section 5 summarises the data presented in this paper, discusses the nature and characteristics of data on historic railway loads, and suggests further data uses and directions of research in estimating the service life of bridges.

2. Historic axle loads

2.1. Locomotives

The data on locomotive axle loads have been primarily gathered from Aspenberg (2001), Bjerke, Hansen, Johansson, and Sando (1987) and Norges Statsbaner (1900-1996b). Figure 1 shows the evolution of the maximum axle load and the relationship with the maximum secondary axle loads of locomotives used in the Norwegian railway network.

The maximum axle load of locomotives has increased, going through roughly four different levels during the railway's history. Prior to 1900, the maximum axle load of locomotives was 11 t. Around the turn of the century, the maximum axle load increased rapidly to 15 t. In the fifties, the axle loads of trains increased again to 18 t, with the



(a) (b) (c)

Figure 1. (a) The evolution of the maximum axle load of locomotives, (b) the distributed load across buffers and (c) the relationship between axle loads on the driving and secondary axles of the locomotive, i.e., the leading, trailing and tender axles. The filled markers indicate locomotives used on the iron ore lines. Grey markers indicate narrow gauge locomotives.

maximum axle loads continuing to rise, reaching 21 t for today's locomotives. Note that locomotives used for the iron ore lines at Ofot- and Dunderlandsbanen generally have the highest loadings; however, the movements of such locomotives are restricted to the mentioned lines. Such locomotives are therefore not considered further in the presented description. The delivery year does not necessarily indicate that the locomotive was in widespread use throughout the railway network, as the first delivery was often used to test the design before making further acquisitions.

An interesting pattern of the distributed loading of locomotives is shown in fig. 1b.

The distributed load increased significantly around 1900 and approached 7 t/m around 1920 for several steam locomotives. The distributed loading of subsequent electric and diesel locomotives used in regular traffic has not surpassed 6 t/m, i.e., the distributed loading over the buffer length was the highest for steam locomotives built after 1900.

Figure 1c shows that the driving axles are generally the most heavily loaded axles of locomotives. This is explained by the tractive effort of a locomotive being limited by the friction between the driving axles and the rails. The loads of leading and trailing axles on locomotives are generally in the range of 50 % to 100 % of the driving axle load, with a modulus of 75 % between leading/trailing and driving axle loads being a reasonable assumption based on a visual inspection of the figure.

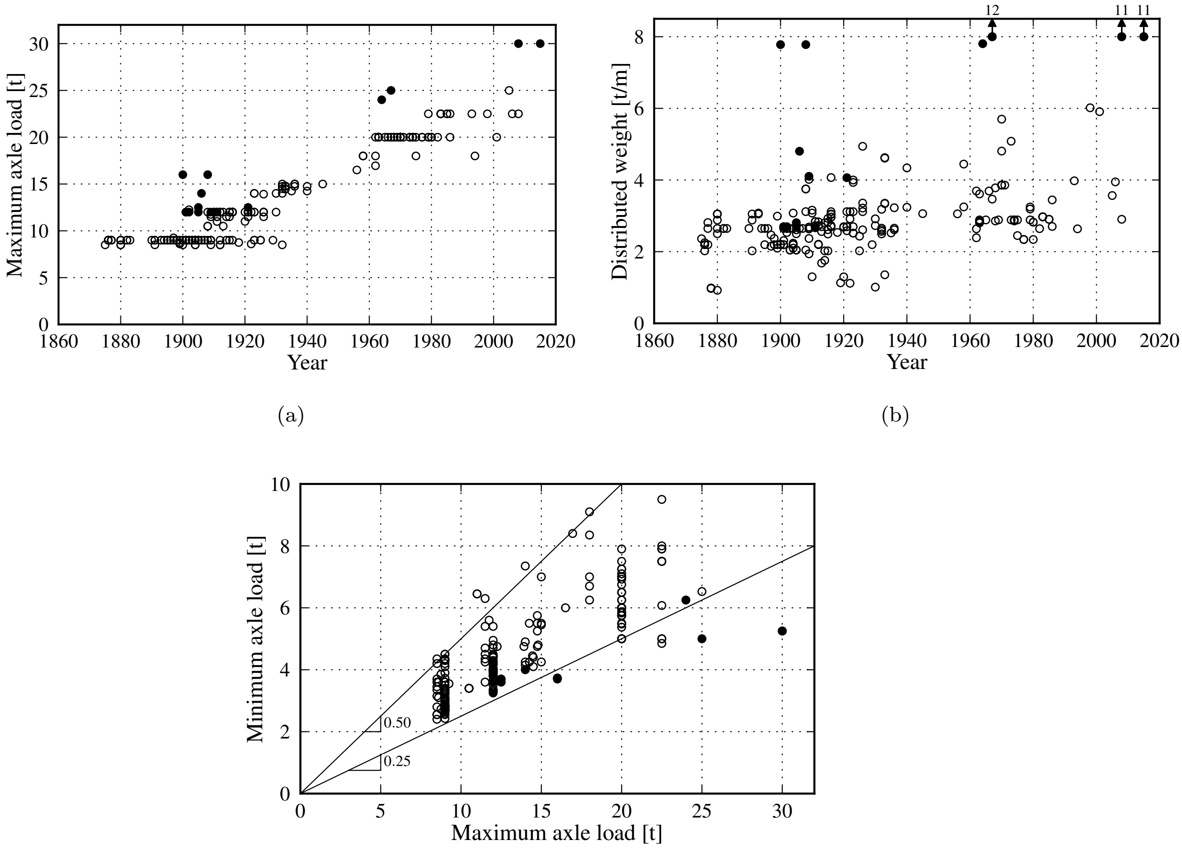
The figure also shows that the tender axle load can be higher than that of the driving axle for certain locomotives. Note that the tender axle load changes as stores of water and coal are depleted; hence, the tender axle loads presented in the figure represent the upper bounds.

The narrow-gauge locomotives (grey markers) have a significantly lower maximum axle load than their standard-gauge counterparts. Data on the evolution of the axle loads of narrow-gauge freight and passenger wagons have not been found; however, as narrow-gauge locomotives have significantly lower axle loads than standard-gauge locomotives, it can also be argued that the wagons used on narrow-gauge lines similarly had lower axle loads than standard-gauge wagons.

2.2. Freight wagons

Historic data have been compiled from Norges Statsbaner (1900-1996a), including amendments that were published periodically during the railways' history. The newest data have been obtained from the national vehicle register of rolling stock. Figure 2 depicts the axle loads of freight wagons.

The maximum load imposed by Norwegian freight wagons changed in stages. Prior to 1900, the maximum axle loads of freight wagons in the general railway network was 9 t, increasing to 12 t at the turn of the century. In 1932, the first wagons with 15 t axle loads were delivered and put into service. From 1956, a new class of freight wagons was introduced with 18 t axle loads.



(a) (b)

(c)

Figure 2. (a) The evolution of the maximum axle weight, (b) the evolution of the distributed load across buffers, and (c) the relationship between the axle loads of full and empty freight wagons. The filled markers indicate freight wagons that were used on iron ore lines.

After the Second World War, UIC introduced a series of standard two-axle freight wagons together with the standard running gear. The standardised single-axle and bogie suspension had an axle load capability of 20 t (Jönsson, 2002). The Norwegian rail administration adopted standardised freight wagons and running gear in 1966, while the previously classified 18 t wagons were modified to comply with the UIC standard.

The standardised UIC running gear of freight wagons was upgraded during the 1980s to 22.5 t after extensive experimental measurements had been performed in the European railway network (Iwnicki, Stichel, Orlova, & Hecht, 2015). Since the introduction of standardised freight wagons and running gear, the variation in the maximum axle loads of freight wagons has declined, as shown by fig. 2a.

The highest permissible axle loads of wagons registered to date are those of special flat wagons built and registered in 2003. Such wagons have the maximum axle load of 25 t and are used for timber transport on certain lines in the southeastern parts of the railway network under a dispensation from the general permissible loads.

Figure 2b shows that the maximum distributed loading of freight wagons was below 3 t/m until 1910, 5 t/m until 1970 and below 6 t/m until 1998, i.e., the maximum distributed loading of freight wagons increased over time.

Figure 2c depicts the relationship of the axle loads between full and empty wagons. The axle load of an empty wagon can be assumed to be 25 % to 50 % of the maximum axle load. Certain wagons have a higher than 25 % maximum axle load, as certain types of goods require special heavier wagons, e.g., an empty insulated thermal wagon weighs more than a flatbed wagon for intermodal transport.

2.3. Passenger wagons and multiple units

The historic data on passenger wagons and multiple units have been compiled from Norges Statsbaner (1900-1996c, 1954-1996). The axle load of a passenger wagon is determined by the number of passengers present in the wagon. The maximum number of passengers is determined by the number of seats n_{seats} and the available area for standing passengers. The available area of a wagon comprises the aisle and the areas near the wagon entrances. Herein, two passengers per metre are assumed to be standing in the buffer of length L_{buffer} to account for non-seated passengers. Hence, the total number of passengers $n_{\text{passengers}}$ of a fully loaded passenger wagon is given by eq. (1)

$$n_{\text{passengers}} = n_{\text{seats}} + 2 \cdot L_{\text{buffer}} \tag{1}$$

Figure 3 shows the evolution of axle loads and the relationship between the axle loads of full and empty passenger wagons and motorised units, assuming that each passenger weighs 75 kg.

The maximum axle weight of passenger wagons was approximately 9 t until 1910, subsequently increasing to approximately 11 t by the 1950s, when a series of wagons

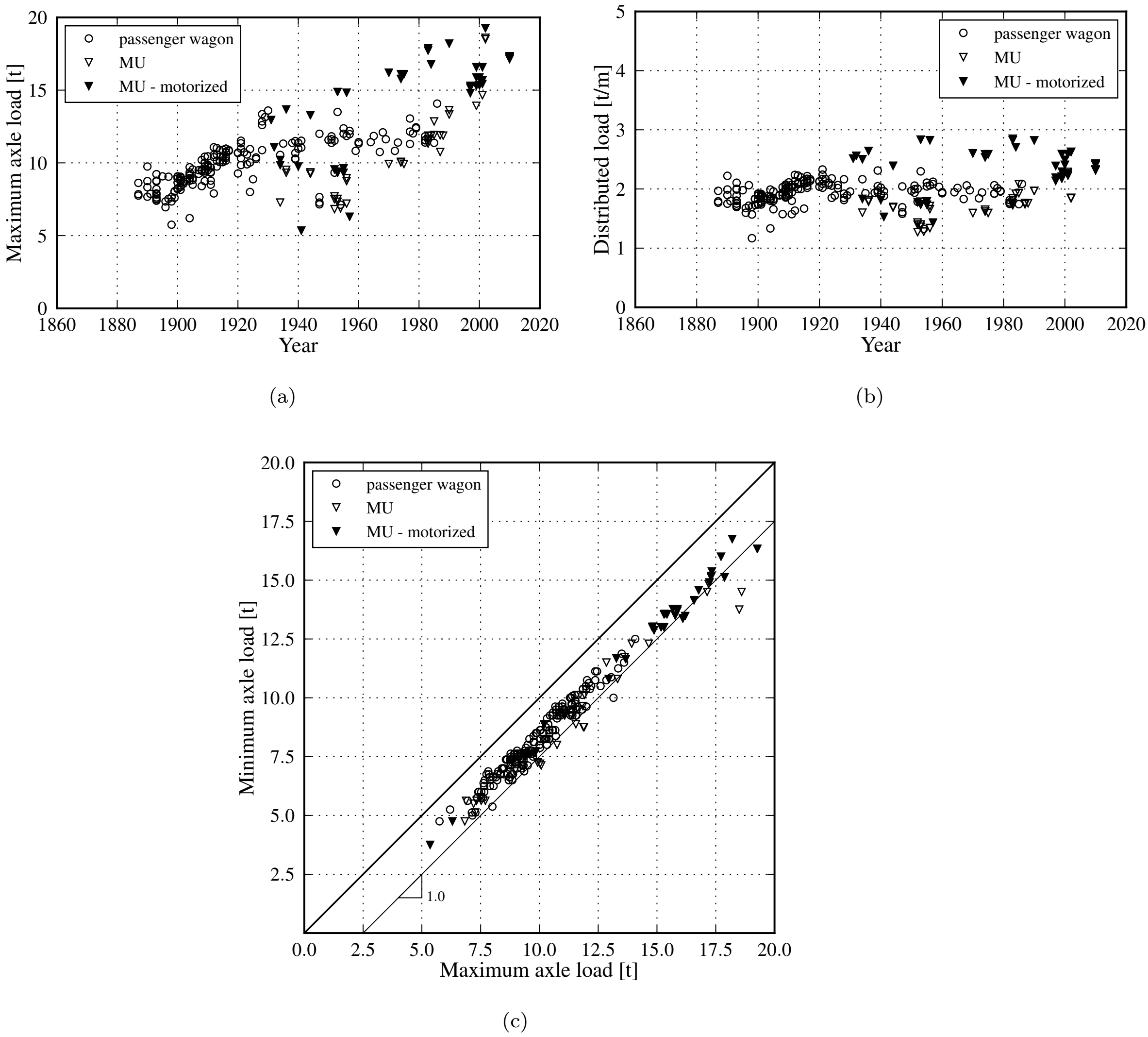


Figure 3. (a) The evolution of the axle loads of passenger wagons and multiple units, (b) the distributed load across the buffer length, and (c) the relationship between the axle loads of empty and full units. The total number of passengers in each wagon is estimated by eq. (1), while the passenger weight is assumed to be 75 kg.

with steel bodies was introduced with 12 t axle load. The maximum axle load of passenger wagons has generally remained around 12 t until the present, with the exceptions to this general description being a series of two-axle steel wagons in 1928 that were not used extensively for transportation, a restaurant wagon in 1953 and a sleeper wagon in 1986. The sleeper wagon of NSB type 7 is still commonly used in long-distance overnight trains.

The first multiple unit was introduced in 1931; fig. 3a shows that motorised units have the highest axle loads among wagons used for passenger transport. The non-motorised multiple units have historically had the same axle loads as regular passenger wagons; however, starting from 1990, the non-motorised multiple unit wagons have had higher axle loads. The axle loads of motorised multiple units are roughly comparable to those of locomotives of the time.

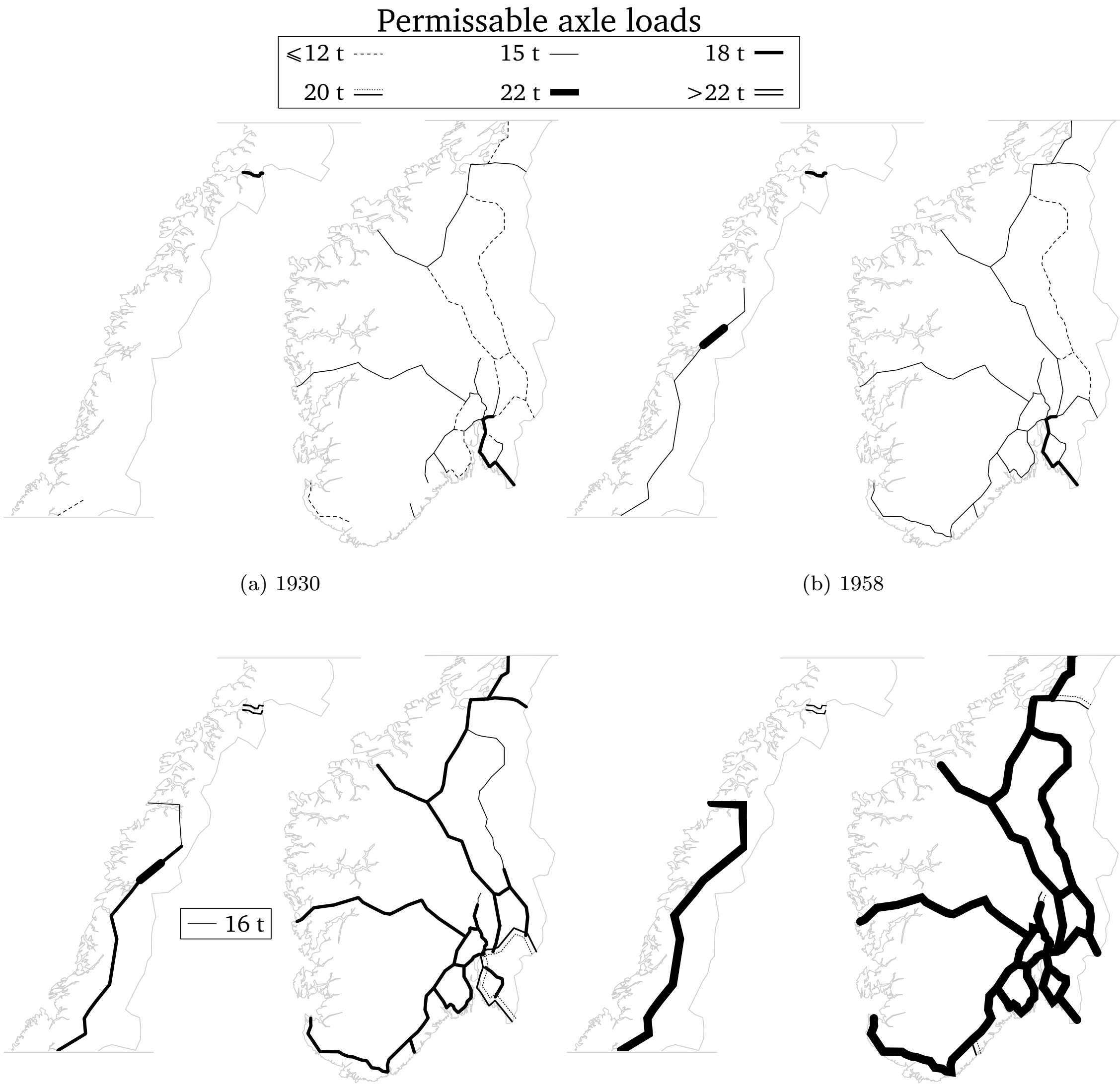
The distributed loading of passenger wagons depicted in fig. 3b has remained relatively unchanged throughout the entire railways' history at around 2 t/m. The distributed load of a motorised multiple unit followed the same trend, i.e., the distributed loading has remained unchanged slightly below 3 t/m.

Figure 3c shows that subtracting 2.5 t per axle from the maximum axle load of a wagon yields a good approximation of an empty wagon weight for regular passenger wagons and motorised wagons. The weight of 2.5 t per axle corresponds to approximately 130 passengers of average weight of 75 kg. The number of passenger seats in passenger wagons has varied between 20 and 80 throughout the entire history, while certain newer multiple units accommodate up to 120 seated passengers.

2.4. Permissible loads on a track

The permissible load on a particular line during a period provides an upper bound on the load experienced by bridges along the line. The data are gathered from network statements issued by the infrastructure owner, i.e., historically Norges Statsbaner (1950-1996), and, since 2003, from the *network statement* available under EU Directive 2012/34/EU. Figure 4 shows the permissible axle loads in the railway network in various years.

Permissible axle loads ranged from 7 t to 17 t in the first half of the previous century. The pattern became more uniform around 1950, with the permissible axle load being 15 t as a general rule. It remained so until around 1960, when the *Modernisation and rationalisation*-plan (Hovestyret for Statsbanene, 1958) (MR-plan) was ordered and put into effect by the Norwegian parliament. Higher axle loads and speeds were two of the explicit goals of the MR-plan to improve the railways' competitiveness relative to other modes of transportation. According to the MR-plan, the axle loads were increased to 18 t, remaining at that level until 1984, as shown in fig. 4c. Another change in permissible axle load was made in 1985 to 20.5 t, with a further increase



(a) 1930

(b) 1958

(c) 1984

(d) 1996

Figure 4. Depictions of permissible axle loads on the main lines of the Norwegian railway network.

to 22.5 t in 1989. By 1996, most of the Norwegian railway network had reached the current standard with the permissible axle load of 22.5 t.

2.5. Train speed

The train speed affects both the quasi-static and dynamic components of the load exerted by the train on the infrastructure.

2.5.1. Locomotive speed

Figure 5 shows the maximum speed of locomotives and motorised units throughout the railways' history. Prior to 1900, the maximum speed of locomotives was 70 km/h. The fastest steam locomotive was NSB Type 30 with the nominal top speed of 90 km/h, introduced to the network in 1913. Diesel- and electric-powered locomotives reached speeds of 100 km/h around 1940. After 1950, the maximum speed increased until reaching the maximum speed of 200 km/h of modern electric locomotives and multiple units. Historically, there has not been a clear difference in speed between locomotives and motorised units, with the fastest locomotives having approximately the same top speed as motorised units.

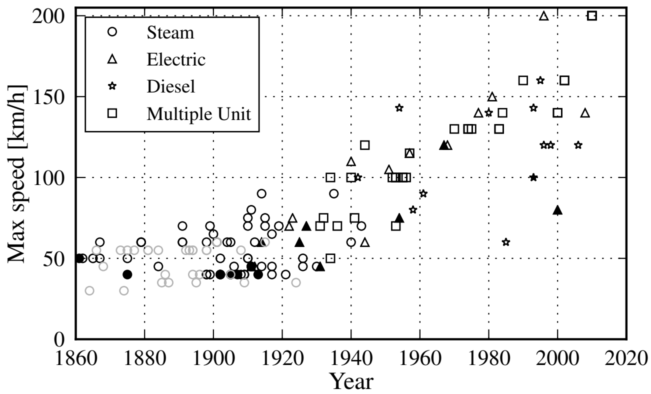


Figure 5. The maximum speed of locomotives and multiple units. The filled markers indicate locomotives used on the iron ore lines. Grey markers indicate narrow gauge locomotives.

2.5.2. Permissible speed on a track

The maximum speed of the locomotive is not the only governing factor of the maximum train speed. The infrastructure owner also imposes speed restrictions to ensure a safe, comfortable and economic operation of the infrastructure.

Table 1 shows the maximum permissible train speed imposed by the infrastructure owner's regulations. The speed limits for passenger trains have generally been significantly higher than those for freight trains. This is simply due to different operating conditions, e.g., the axle loads being much higher for freight trains. No representative data on infrastructure-imposed speed limits prior to 1950 have been found.

Table 1. The maximum speeds of passenger and freight trains according to the infrastructure owner's regulations. Speeds are given in [km/h].

Train\Year	1950	1970	1990	2000	2016
Passenger	90	120	130	160	210
Freight	65	80	80	80	100

3. Rolling stock geometry and design

3.1. Geometry and design of locomotives

3.1.0.1. Design. The classification system presented in International Union of Railways (1983) is adopted in the following discussion on locomotive design and geometry. Figure 6 shows the number of driving axles and the locomotive class as a percentage of the total number of locomotives used in regular traffic by year.

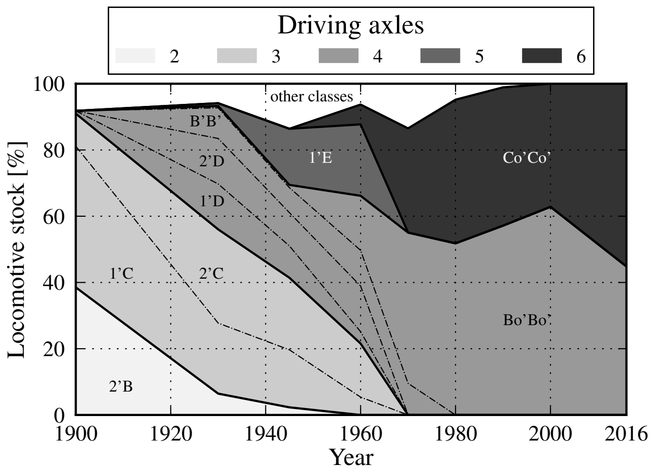


Figure 6. The axle arrangement and the number of driving axles of locomotives used in regular traffic. The figure includes all steam locomotives with tenders and electric/diesel locomotives with more than three driving axles. Motorised units are not represented in the figure.

Prior to 1900, locomotives had at most three driving axles, increasing to four at the turn of the century, five around 1930 and eventually six around the start of the second half of the previous century.

The reason for increases in the number of driving axles during the railways' history relates to the demand for higher axle loads and train speeds. The maximum tractive effort a locomotive can generate to pull a set of wagons is limited by the friction force between the driving wheels and the rails. To increase the tractive effort of a locomotive, given the restriction on the permissible axle load on the track, it is necessary to increase the number of driving axles.

Figure 6 includes only steam locomotives with tenders, i.e., a locomotive connected to a wagon with a supply of fuel and water. Tender locomotives had a larger range and were the primary steam locomotive type used in regular traffic. Tank steam locomotives, on the other hand, were primarily used in shunting service, although some tank locomotives were also used in regular service trains, either as assistance locomotives on steep ascents or in local passenger traffic around major cities, with additional details on such uses provided in the following subsection on locomotive geometry. The majority of steam locomotives had one or two lead axles in addition to the driving axles.

Electric and diesel power locomotives used in regular traffic featured four and six driving axles. The earliest electric locomotives had both leading and trailing axles; however, the modern electric and diesel locomotives are all without leading or trailing axles. In steam locomotives, the driving axles are in one group, while in electric and diesel locomotives, they are generally grouped into two bogies.

3.1.0.2. Geometry. The geometry of Norwegian locomotives varies according to the locomotive's design. Table 2 shows the dimensions of locomotive classes identified in the previous section. Note that the steam tank locomotive, class 1'C1't, is also included, as it was used in local passenger trains around the larger cities (Bjerke et al., 1987) before multiple units took over the task as suburban trains.

Perhaps the overall greatest deviation in the dimensions of steam locomotives is observed in the smallest locomotives, i.e., class 2'B-2 and 1'C-3 locomotives. Such locomotives are the oldest representatives of a period when the standardisation across different lines was not yet implemented.

The most significant deviations among the other steam locomotives are observed in the distances between different axle types, i.e., the distances between the leading wheel(s) and the driving wheels, and between the driving wheels and the tender wheels. The deviations in the distances between driving wheels is generally small.

Table 2 also shows that the driving axles on steam locomotives are in general more closely spaced than those on electric/diesel locomotives. Driving axles on steam engines

Table 2. Geometry of the most numerous locomotives of each class. Coverage indicates the percentage represented by the respective locomotives in the total number of locomotives of the class. The axle load column refers to the axle loads on the driving axles for each geometry (a-f). Figure 6 and table 3 provide information on time periods that the locomotives were operating within.

Class	Geometry	Coverage	Axle load (a/b/...)
	Steam locomotives –1970		
1'C1't	a 1.4 2.6 1.8 1.8 2.2 1.5	43%	15
2'B-2	a 1.0 1.7 1.8 2.1 2.2 2.7 1.2 b 1.0 1.4 2.0 1.9 2.2 1.8 1.3 c 1.3 2.0 2.0 2.2 2.7 2.5 1.7	88%	10 / 7 / 11
1'C-3	a 1.3 2.6 1.7 1.7 2.6 1.5 1.5 1.5 b 1.3 1.8 1.6 1.8 2.5 1.4 1.2 1.4 c 1.3 2.5 1.7 2.1 2.3 1.5 1.5 1.5	90%	11 / 7 / 10
2'C-2'2'	a 1.5 2.3 1.8 1.8 1.8 2.6 1.6 1.3 1.6 1.2 b 1.3 2.1 1.4 1.7 1.7 2.0 1.6 1.2 1.6 1.1	83%	15 / 12
1'D-2'2'	a 1.5 2.5 1.4 1.4 1.4 2.6 1.6 1.3 1.6 1.2 b 1.6 2.6 1.4 1.4 1.4 2.7 1.6 1.3 1.6 1.2 c 1.5 2.5 1.4 1.4 1.4 2.8 1.6 1.3 1.6 1.2 d 1.5 2.5 1.4 1.4 1.4 3.0 1.6 1.3 1.6 1.2	87%	12 / 14 / 15 / 15
2'D-2'2'	a 1.6 2.1 1.4 2.0 1.5 1.5 2.4 1.6 1.6 1.6 1.4 b 1.4 2.1 1.4 1.9 1.5 1.6 2.2 1.6 1.3 1.6 1.2	100 %	15 / 12
1'E-2'2'	a 2.0 2.6 1.6 1.6 1.6 1.6 3.9 1.8 2.3 1.8 2.0	92%	15
	Diesel/electric locomotives –1980		
B'B'	a 2.0 3.0 2.8 3.0 2.0 b 2.0 3.2 2.7 3.2 2.0	100 %	15 / 12
Bo'Bo'	a 2.0 3.0 4.4 3.0 2.0 b 2.2 3.2 4.1 3.2 2.2	94 %	16 / 18
Co'Co'	a 2.2 2.0 2.0 6.3 2.0 2.0 2.2 b 2.8 1.8 1.8 4.8 1.8 1.8 2.8	100 %	17 / 18
	Diesel/electric locomotives 1980–		
Bo'Bo'	c 2.4 2.6 8.4 2.6 2.4 d 3.0 2.4 6.6 2.4 3.0 e 2.6 2.7 5.0 2.7 2.6 f 2.9 2.6 7.8 2.6 2.9	81 %	21 / 21 / 20 / 21
Co'Co'	c 2.6 1.8 2.1 7.9 2.1 1.8 2.6 d 2.4 1.8 1.8 11.0 1.8 1.8 2.4 e 2.1 2.0 2.1 9.0 2.1 2.0 2.1 f 2.6 1.8 2.0 7.9 2.0 1.8 2.6	92 %	20 / 21 / 21 / 19

lead/trail drive tender

are all coupled together, while those on electric and diesel locomotives are powered by at least two separate engines. A comparison of the 1'D-2'2' steam locomotive with the B'B' diesel/electric locomotive illustrates this point clearly, as the maximum distance between driving axles on the steam engine is 1.4 m, compared to the minimum distance of 3.0 m for the B'B electric and diesel/locomotives. The distributed load intensity for the steam locomotive may therefore be higher than that for the diesel/electric counterpart, even if the axle loads are lower.

The axle loads of the driving axles are also included in table 2. The axle loads of the lead/trail and tender axles of steam locomotives can generally be obtained from fig. 1c, i.e., the lead/trail and tender axle loads can be assumed to be 75 % of the driving axle load.

3.2. Geometry and design of wagons

The geometry of wagons is described by the distance from the buffer to wheelset centre a, the centre-centre distance between wheelsets b, and the distance between wheels in a bogie wheelset c, as shown in fig. 7. Figure 7 also shows the most common examples of wagon designs: two-axle wagons, (four-axle) bogie wagons and (six-axle) Jacobs bogie wagons.

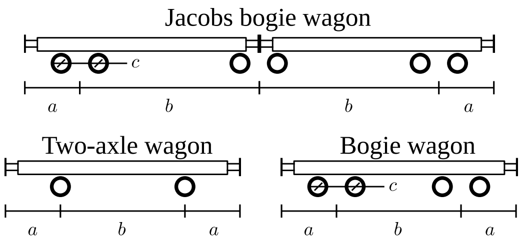


Figure 7. Geometry of two-axle wagons, bogie wagons and Jacobs bogie wagons.

3.2.1. Freight wagons

3.2.1.1. Design. Two-axle and bogie freight wagons have been in service throughout the history of the Norwegian railway network. The Jacobs bogie wagons did not join the rolling stock until the very end of the 20th century. Figure 8 shows the relative number of wagons of each design among freight wagons since 1900.

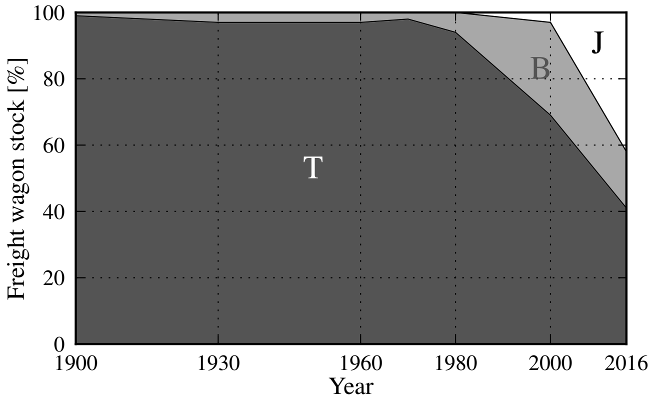


Figure 8. Shares of two-axle (T), bogie (B) and Jacobs bogie (J) freight wagons available in the rolling stock.

Between 1900 and 1970, the two-axle freight wagons dominated the rolling stock. Around 1970, flat bogie wagons were introduced for intermodal transport, i.e., semi-trailer and container transport. During the 80s, bogie wagons were also introduced for other types of freight transport, with approximately 30% of the rolling stock in 2000 being bogie wagons. In 1993, the Jacobs bogie wagon was introduced into the freight rolling stock, becoming popular quickly due to the possibility of carrying full length semi-trailers, as well as combinations of conventional-length containers. The current national vehicle register shows that approximately 40% of wagons are two-axle wagons, 20% are bogie wagons and 40% are Jacobs bogie wagons.

3.2.1.2. Geometry. The right side of fig. 9 shows the geometry data for freight wagons. In general, the maximum length of freight wagons increases over time. Comparison of the changes in the dimensions of two-axle wagons in fig. 9 to the evolution of axle loads in fig. 2a makes it possible to identify the introduction of new 'generations' of wagons around 1930, 1960 and 1980.

The changes in the dimensions of bogie and Jacobs bogie wagons are not as clear as those of two-axle wagons. This is likely explained by the primary freight type design being two-axle wagons prior to the introduction of standardised wagons by UIC in the 1960s. The bogie wagons were not developed and used in regular traffic and therefore were not as diversified as two-axle wagons.

Note that the buffer–wheelset distance a and the wheel distance c in a bogie

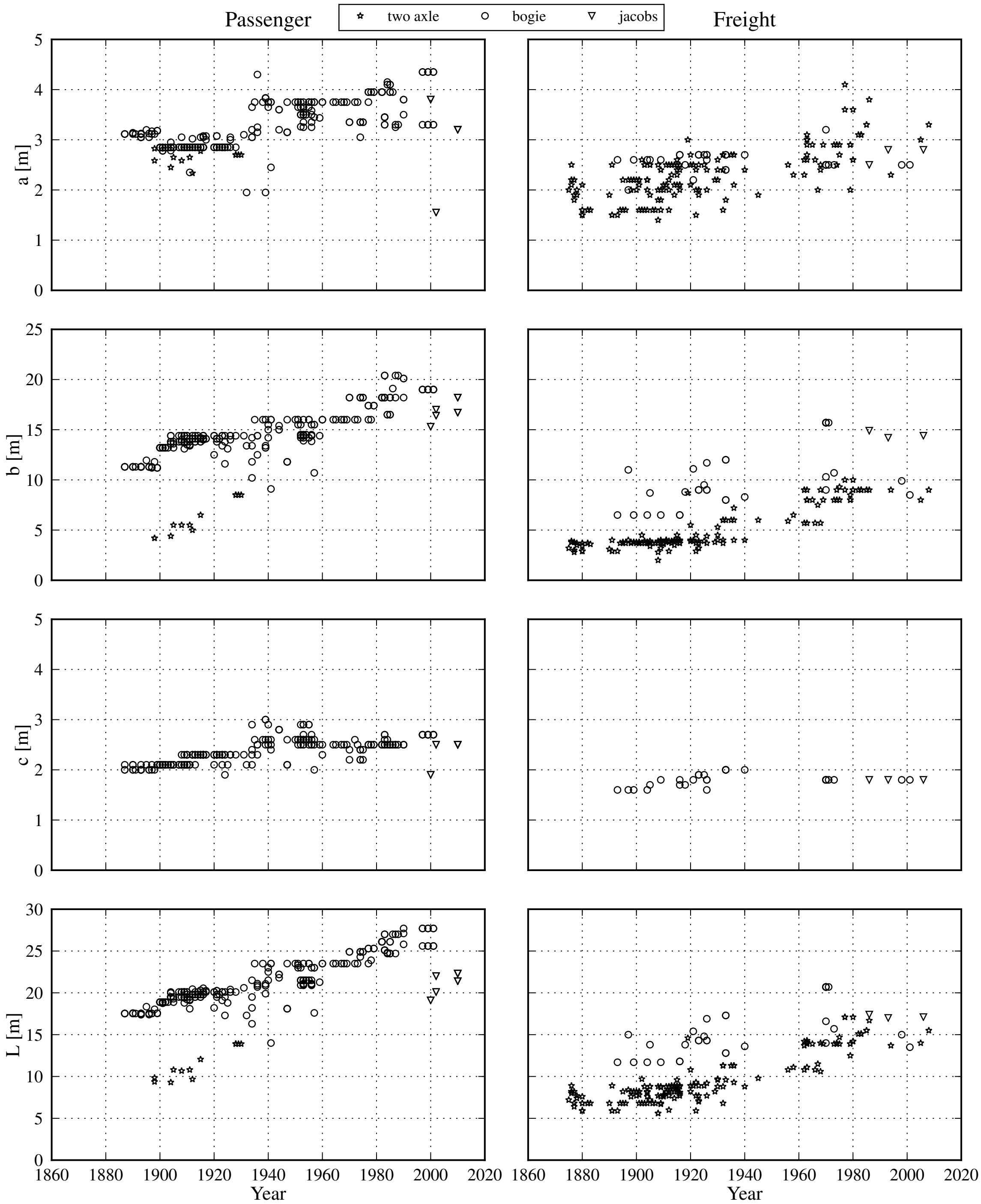


Figure 9. Geometry of passenger wagons and multiple units (left) and freight wagons (right). The total length L of wagons is across the buffers for two-axle and bogie wagons, in contrast to the end– to mid–buffer measurement for Jacobs wagons.

for bogie and Jacobs bogie freight wagons remained unchanged for the last part of the previous century at $a \approx 2.5\,\text{m}$ and $c \approx 1.8\,\text{m}$. As bogie and Jacobs wagons were not used extensively until the last part of the previous century, the geometry of such wagons can be considered to only vary with b.

Figure 10 shows the variables a and b for freight wagons. For two-axle wagons, there is a positive correlation between the two variables, i.e., an increasing b implies an accompanying increase of a. For bogie and Jacobs bogie wagons, there is no apparent correlation between these variables. Although not presented in any figure, the data show no clear correlation between a and c or between b and c for freight wagons.

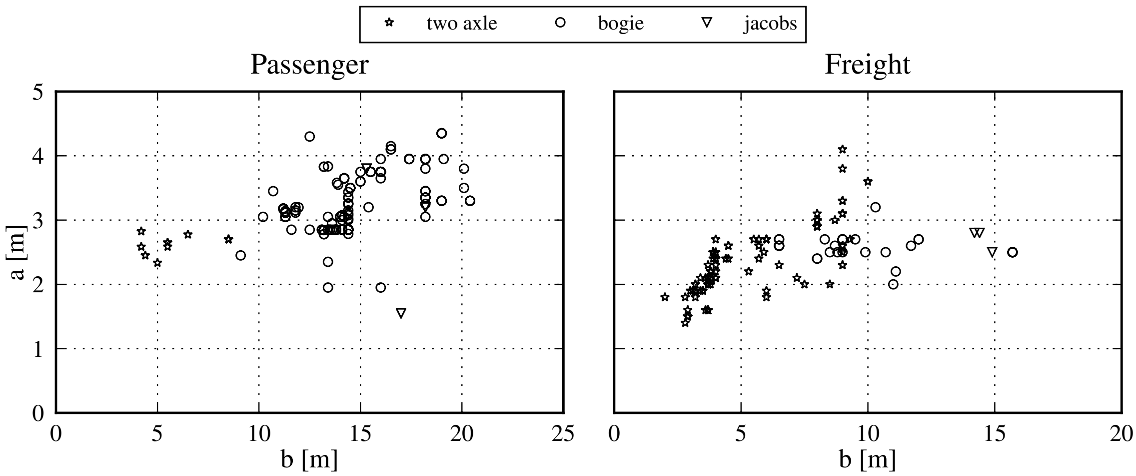


Figure 10. Geometric variables a and b for passenger wagons and multiple units (left) and freight wagons (right). Similar plots have been constructed for $a - c$ plotted against $b - c$; however, no correlation structure was observed.

3.2.2. Passenger wagons and multiple units

3.2.2.1. Design. The designs of passenger wagons and multiple units have largely remained the same. Note that the motorised wagons of multiple units do not generally differ from non-motorised wagons. In 1903, two-axle and bogie wagons each constituted approximately one half of the available passenger rolling stock. This changed rapidly, with passenger wagons and multiple units in use after 1900 being almost exclusively four-axle bogie wagons. Compared to two-axle wagons, bogie wagons provide the passengers a smoother and more comfortable ride. Jacobs bogie wagons are found on the newest multiple units, i.e., multiple units introduced after 2003. The following discussion focuses on the bogie and Jacobs bogie wagons, as these are the wagons used for regular traffic. Data for two-axle wagons are, however, included in fig. 9 for completeness.

3.2.2.2. Geometry. Figure 9 shows that the overall dimensions of passenger wagons and multiple units increased over time. There are several distinct steps in the evolution of the dimensions. The change around 1900 should be considered together with the increased axle loads of passenger wagons, as displayed by fig. 3a, and is likely to be due to an increase in permissible axle loads around 1900. A significant increase in dimensions can also be observed around 1930 due to a change from wood to steel for the material used to construct passenger wagons. Similar increases in a, b and L can be observed around the mid-70s and 80s with the introduction of two entirely new classes of passenger wagons, NSB type 5 and 7. A part of the modernisation plan during the 60s, 70s and 80s involved increasing the overall speeds on train lines, again requiring the removal of small-radii curves and track profile that previously limited the wagon dimensions. Figure 10 shows no strong correlation between the geometric variables a, b, and c for passenger wagons.

4. Train geometry and composition

The particular composition of a train, i.e., the locomotive and the wagons, defines the distribution and magnitude of the load and has a large influence on the response history the train produces when it passes a bridge. This section presents the relevant data on the composition of trains.

4.1. Mixed train traffic

Trains can be categorised as passenger, freight or mixed trains. The latter consist of both passenger and freight wagons and have been used on lines with traffic volume too low to support passenger-only or freight-only trains. The use of mixed trains during the initial years after a line opened is a common feature of all lines.

The use of mixed trains was already limited in 1935, with only 6 % of the total train running distance performed by mixed trains (Central Bureau of Statistics of Norway, n.d.). The last mixed trains were in service until 1968 (Norges Statsbaner, 1988). Mixed trains unfit to freight and passenger traffic, as their use places restrictions on the stopping frequency and loading time of freight and extends passengers' transit time. On any line with *significant* passenger or freight traffic, the mixed train type was abandoned in favour of freight-only and passenger-only trains. It is therefore reasonable to assume that a significant portion of passenger and freight transport has been performed by passenger-only or freight-only trains throughout most of the railway history.

4.2. Train traction type

Figure 11 depicts the use of various types of tractive vehicles as a share of the total running distance of such vehicles.

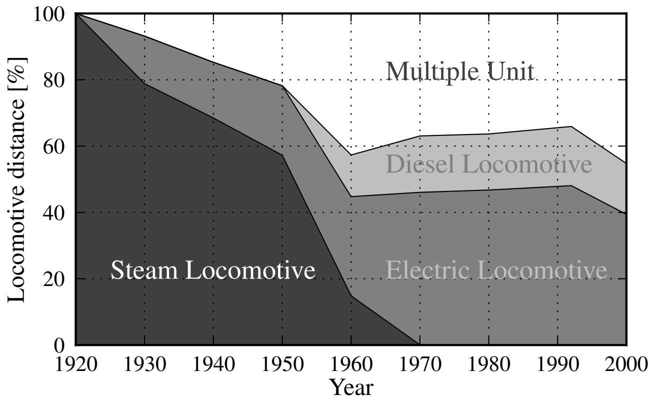


Figure 11. Various tractive types' shares of the total running distance. Steam, electric and diesel locomotives are used in both passenger and freight transport, while multiple units are used solely for passenger transport. Data for the period after 1998 have not been obtained.

The steam locomotive was the only type of tractive vehicle used in the Norwegian railway network until 1923. Electrification continued over the following decades until 1970, when Dovrebanen was fully electrified (Aspenberg, 2001). In 1954, diesel locomotives were put into regular service, while, at the same time, the rail administration officially abandoned the steam engine technology, with the last steam engine being decommissioned in 1971.

Multiple units were introduced around 1930 and quickly became an important part of the tractive vehicle stock, especially for local and shorter-distance passenger traffic. From 1960, multiple units were also used in regional trains and are currently important to both local and regional passenger traffic, with approximately 40 % of all tractive distance since 1960 being provided by multiple units.

4.3. Number of wagons in trains

The number of wagons in a train is governed by economic, practical and technical factors. Historic data on train (locomotive) running distance and axle running distance for passenger and freight wagons are available in Central Bureau of Statistics of Norway (n.d.) and Norges Statsbaner (1988, 1996-1998) for the period 1935–1998. An estimate of the average number of axles in trains can therefore be obtained by dividing the axle running distance by the train running distance. Figure 12 shows the average number of axles estimated using the data obtained from the above source.

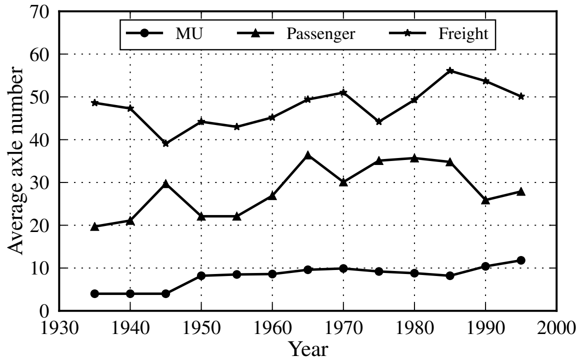


Figure 12. The average axle number of trains, estimated by dividing the axle running distance by the train running distance for each train type.

The lengths of all train types tend to increase, with the freight trains having the most axles. The average number of axles of freight trains varied between 40 and 50 prior to 1980 and from 50-55 after 1980. As the majority of freight wagons prior to 1980 were two-axle freight wagons, as shown by fig. 8, the average number of wagons of freight trains has ranged between 20 and 25 two-axle wagons. The increase in the use of bogie wagons from around 1980 might also explain the increase in the number of axles after 1980. For the period 1980–2000, an estimate of the number of wagons can be obtained by assuming 80% two-axle wagons, 20% bogie wagons and 55 axles, resulting in an average of 21 wagons in freight trains. No data for the average number of axles are available for the period after 2000, while the composition of the available rolling stock changed significantly when Jacobs bogie wagons were introduced; however, as the average number of wagons during most of the railways' history has been in the range of 20–25, it is reasonable to assume that the average number of wagons in freight trains is presently similar. The average number of wagons in freight trains for the period after 1985 is therefore also in the range of 20 to 25.

Passenger trains and multiple units has generally been four-axle bogie wagons throughout the entire railways' history. Figure 12 indicates that passenger trains had close to 20 axles, or 5 wagons, prior to 1960. In the period between 1960 and 1985, the average number of axles on passenger trains was between 30 and 35, or approximately 8 wagons. After 1985, the average number of wagons decreased to approximately 7 wagons.

The average number of axles on multiple units has increased steadily from 4 in the 1930s to 8 in 1950 and 12 in the 1990s, corresponding to one wagon prior to 1950, two wagons after 1950, and three wagons after 1990.

4.3.1. Limits on the number of wagons in trains

The lower limit on the number of wagons in a train is determined by the transport value of the goods being transported. The first multiple units consisted of a single wagon, while the current shortest multiple unit consists of only two wagons. Prior to multiple units, i.e., before 1930, locomotive-hauled passenger trains were used in suburban service; it is reasonable to assume that such suburban trains consisted of one or two passenger wagons when multiple unit length after 1930 is considered. Most multiple units could be joined together and driven in tandem, with the maximum length of multiple units therefore being twice the length of a multiple unit of the time. Furthermore, assuming that multiple units were used on lines with the lowest traffic intensity, the minimum number of wagons in locomotive-hauled passenger trains can be estimated by the maximum multiple unit length, i.e., 2 wagons during 1900–1960, 3 wagons during 1960–1985 and 5 wagons after 1985. The lower limit on freight wagons is more challenging to estimate due to a lack of relevant data; however, considering that the average number of freight wagons is three to four times the average number of passenger wagons, a minimum of 10 freight wagons can be assumed for freight trains throughout the railways' history.

The brake system, the capacity of coupling between wagons, the platform length at stations and the passing loop length of single-track lines all influence the maximum length of trains (Heie, 1941; Norges Statsbaner, 1950-1996), with all such factors considered in the following discussion of freight and passenger train length.

For passenger trains, the maximum number of axles has primarily been restricted by the braking capacity of the train. The maximum length due to brake conditions depends on the maximum allowable speed, with higher speeds demanding a stronger brake capacity. Passenger trains have during the history of railways been limited to approximately 80 axles, i.e., 20 four-axle bogie wagons, at a speed of 50 km/h.

For freight trains, the maximum train length has been approximately 50 wagons, as determined by the passing loop length of the track and the coupling capacity between the wagons in the train. Technically, neither factor can be considered to impose a strict or hard limit on the train length. For instance, the issue of coupling capacity between wagons can be mitigated by introducing an assistance locomotive at the middle or end of the train at the steepest ascents (Norges Statsbaner, 1950-1996). Similarly, the passing loop length only restricts the shorter passing train, i.e., the shorter train is diverted to the passing loop and waits until the longer train passes (Heie, 1941). Practically, however, it is preferable to avoid the use of assistance locomotives due to the added cost of an extra locomotive and driver; additionally, factors other than train length have to be considered when scheduling the use of passing loops, e.g., express passenger trains having a higher priority than freight trains such that the freight train must be diverted to the passing loop.

5. Discussion

5.1. Relevance of presented data to actual loads in the railway network

The data presented in this paper is largely based on the permissable loads on infrastructure and rolling stock. In theory, the permissible loads establish the bounds for the loads on the infrastructure. It is, however, important to acknowledge that the actual loads on the infrastructure may exceed these bounds.

The discrepancy between the actual loads and the permissible loads can only be determined by performing measurements on actual traffic. Unfortunately, such measurements are not available for the Norwegian railway network and they are also scarce in the international literature. One exception are axle load measurements reported by James (2003), which indicate that approximately 2.5% of all axles exceed the permissible axle load on a line with mixed passenger and freight traffic in the Swedish railway network. Obviously, these results are valid only to the traffic at the specific line and period of acquisition. On lines with system traffic, such as iron ore lines, one might also expect systematic overloading of wagons such that a much larger proportion of the axles exceed the permissible loads. Regardless of the proportion of axles that exceed the permissible loads, it is clear that permissible loads are exceeded by actual loads.

On the other hand, the consequences of significantly exceeding permissible loads on railways are severe. Failure of a bridge due to overloading of wagons or derailment of a train due to high speed are generally catastropic in terms of human life and economic cost. It is therefore reasonable to assume that the maximum loads of actual traffic will be related to the permissible loads on rolling stock and infrastructure.

In any case, without actual load measurements or other available data, permissible loads are the best available estimators for the bounds on actual load conditions in the railway network.

5.2. Evolution of load conditions in the Norwegian railway network

Table 3 shows an overview of the data presented for the general railway network.

5.2.1. Load conditions due to infrastructure and rolling stock

Comparing the maximum axle loads of locomotives, shown in fig. 1a, to permissible axle loads on a track, fig. 4, it is clear that the heaviest locomotives are limited to certain lines of the railway network during their respective periods of service.

Furthermore, a comparison of permissible axle loads and the axle load capacity of

Table 3. Summary of data for the rolling stock and train composition during the history of the Norwegian railways.

Train composition

Period	Train type	Locomotive / Motorised unit	Max speed	Wagon type	Number of wagons, N
–1900	LS	1'C1't	70 km/h	T+B	$\hat{N} = 1, N \in [1, 2]$
	P	2'B-2	70 km/h	T+B	$\hat{N} = 5, N \in [1, 20]$
	F	1'C-3	50 km/h	T	$\hat{N} = 20, N \in [10, 50]$
1900–30	LS	1'C1't	75 km/h	B	$\hat{N} = 1, N \in [1, 2]$
	P	2'B-2 | 2'C-2'2 | 2'D-2'2'	90 km/h	B	$\hat{N} = 5, N \in [1, 20]$
	F	1'C-3 | 1'D-2'2	65 km/h	T	$\hat{N} = 23, N \in [10, 50]$
1930–60	LS	B(13, 3.6, 15.0, 2.5)	90 km/h	B	$\hat{N} = 2, N \in [1, 4]$
	P	2'C-2'2' | 2'D-2'2' | B'B'	90 km/h	B	$\hat{N} = 5, N \in [2, 20]$
	F	1'D-2'2' | 1'E-2'2' | B'B'	65 km/h	T	$\hat{N} = 23, N \in [10, 50]$
1960–85	LS	B(16, 3.8, 16.0, 2.5)	120 km/h	B	$\hat{N} = 2, N \in [1, 4]$
	P	B'B' | Bo'Bo'[a-b] | Co'Co'[a-b]	120 km/h	B	$\hat{N} = 8, N \in [3, 20]$
	F	B'B' | Bo'Bo'[a-b] | Co'Co'[a-b]	80 km/h	T + B	$\hat{N} = 25, N \in [10, 50]$
1985–2000	LS	B(18, 3.8, 18.0, 2.6)	160 km/h	B	$\hat{N} = 3, N \in [2, 6]$
	P	Bo'Bo'[a-f] | Co'Co'[a-f]	160 km/h	B	$\hat{N} = 7, N \in [5, 20]$
	F	Bo'Bo'[a-f] | Co'Co'[a-f]	80 km/h	T + B	$\hat{N} = 25, N \in [10, 50]$
2000–	LS	B(18, 3.8, 18.0, 2.6)	160 km/h	B + J	$\hat{N} = 3, N \in [2, 6]$
	P	Bo'Bo'[c-f] | Co'Co'[c-f]	160 km/h	B + J	$\hat{N} = 7, N \in [5, 20]$
	F	Bo'Bo'[c-f] | Co'Co'[c-f]	90 km/h	T + B + J	$\hat{N} = 25, N \in [10, 50]$

B(P, a, b, c) indicates a bogie wagon with axle load P and geometric parameters a, b, c; see fig. 7.
$\hat{N}$ – Overall average number of wagons in a train.
LS – Local suburban, F – Freight and P – Passenger

Wagon load and geometry

			Two-axle (T)		Bogie (B)			Jacobs (J)		
Type	Period	Axle load [t]	a [m]	b[m]	a [m]	b [m]	c [m]	a [m]	b [m]	c [m]
Passenger	–1900	5.0–9.0	2.3–2.8	4.2	3.0–3.2	11.2–11.9	2.0–2.1	-	-	-
	1900–30	5.0–11.0	2.3–2.8	4.4–8.5	2.4–3.1	11.6–14.4	1.9–2.3	-	-	-
	1930–60	6.0–12.0	2.7	8.5	1.9–4.3	9.1–16.0	2.0–3.0	-	-	-
	1960–85	7.5–13.0	-	-	3.0–4.2	16.0–20.4	2.2–2.7	-	-	-
	1985–	8.5–14.0	-	-	3.2–4.3	16.5–20.4	2.5–2.7	1.6–5.6	15.3–18.2	2.5
Freight	–1900	2.3–9.0	1.5–2.5	2.5–4.0	2.0–2.6	6.5–11.0	1.6	-	-	-
	1900–30	3.0–12.0	1.5–2.5	2.5–5.0	2.2–2.7	6.5–11.5	1.6–1.9	-	-	-
	1930–60	3.7–15.0	1.5–3.0	3.5–7.0	2.4–2.7	8.0–12.0	2.0	-	-	-
	1960–85	5.0–20.0	2.0–4.1	5.5–9.0	2.5–3.2	9.0–15.7	1.8	-	-	-
	1985–	5.6–22.5	2.3–4.1	7.5–11.0	2.5	9.0–15.7	1.8	2.5–2.8	14.2–14.9	1.8

Axle loads are limited by the infrastructure for certain lines; see fig. 4

freight wagons shows that both factors have governed the limits on freight train axle loads. For instance, prior to 1930, several lines had permissible axle loads of 15 t, as shown in fig. 4a, while the maximum axle load of freight wagons used in regular service was only 12 t for most of the period, as shown in fig. 2a. On the other hand, figure fig. 4c shows that axle loads were track-limited to 18 t for most of the railway network until 1984, while the capacity of freight wagons was at 20 t since the beginning of 1960.

As the use of passenger wagons has not been restricted by the permissible axle loads on tracks, passenger wagons have been used freely in passenger trains. This freedom does not, however, extend to motorised wagons in multiple units, as certain motorised wagons have levels of axle loads comparable to those of locomotives. Multiple units are therefore also limited to certain lines due to the axle loads of motorised wagons.

Regarding the train speed, fig. 5 and table 1 show that the regulations of the infrastructure owner have limited the speed of both passenger and freight trains during most of the railways' history. Prior to 1950, no representative data on the speed limits on infrastructure has been found. During this period, the maximum speed of locomotives is suggested as the upper limit on the speed of passenger trains, i.e., 70 km/h until 1910 and 90 km/h after 1910. We take into account that locomotives used for freight trains have generally had smaller wheels than those used for passenger trains, i.e., freight locomotives run in a lower gear than passenger locomotives. The maximum speed of freight trains can be assumed at 50 km/h until 1910 and 65 km/h from 1910.

The capacities of both rolling stock and infrastructure influence the load conditions in a railway network and should therefore be considered when establishing a load model for service life assessment.

5.2.2. Differences between passenger and freight trains

Section 2 showed that the axle loads of passenger wagons prior to 1900 were comparable in magnitude to those of freight wagons at 9 t per axle; however, after 1900, the axle loads of freight wagons were considerably larger, with the difference between maximum axle loads of passenger and freight wagons continuing to grow during the railways' history. Figure 2c and fig. 3c show that the range of axle loads, i.e., the difference between the minimum and maximum axle loads, is much smaller for passenger than for freight wagons. The magnitude and the variation of axle loads have therefore been smaller for passenger than for freight wagons.

The passenger wagons have a design and geometry different from those of freight wagons. Passenger trains have primarily consisted of bogie wagons, while freight trains have historically been composed of two-axle wagons and more recently a mix of all three designs. All dimensions, a, b, c, and L, are generally larger for passenger wagons than for freight wagons, i.e., the geometry of passenger wagons generally differs from that of freight wagons.

The number of wagons in passenger trains has been lower than that in freight trains, while the speeds of passenger trains have been higher than those of freight trains.

The two types of trains also use different locomotives; although many locomotives have been used with both freight and passenger wagons, the locomotives used in the heaviest freight trains have generally had more driving axles than passenger locomotives. Typically, locomotives used in passenger trains have fewer driving axles due to a lower demand for tractive effort. Furthermore, passenger locomotives have favoured axle arrangements that allow higher speeds, e.g., steam locomotives with larger driving wheels and two leading axles for stability (Bjerke et al., 1987).

Since passenger and freight trains differ in axle loads, geometry, design and operation, the response in a structural detail from passenger trains will be different from the response from freight trains.

What does this mean for the fatigue damage introduced by the two train types? This will depend on both the specific detail under investigation and the rolling stock of the period.

First consider a structural detail with a relatively short influence length compared to the axle distance in wagons. This structural detail will be loaded and unloaded by each passing axle, and each axle introduces a stress range proportional in size to the axle load magnitude. A freight train will then tend to introduce more fatigue damage in this detail than a passenger train because of higher axle loads and axle count.

Next consider fig. 13, which shows the moment at midspan of a simply supported beam with length 13m to a sequence of freight and passenger wagons from the period 1930-60, see table 3.

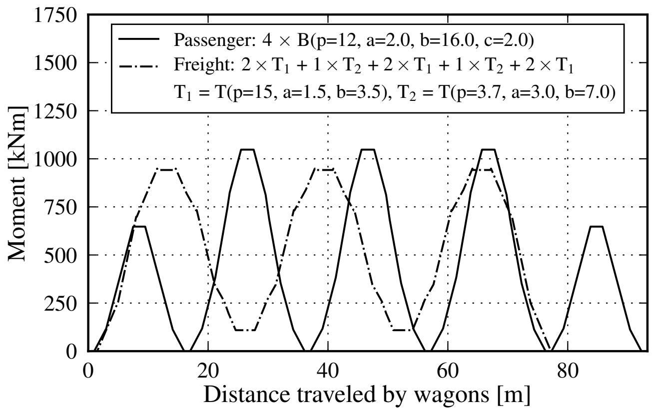


Figure 13. The bending moment at midspan of a simply supported beam with length 13 m to a sequence of wagons from the passenger and freight rolling stock 1930-60. B and T denotes bogie and two axle wagons, respectively.

This structural detail has a longer influence length that allow two bogies in adjacent passenger wagons to load the structure, but at the same time is shorter than the distance between bogies in one wagon. The structural detail is then loaded and completely unloaded, producing large loading cycles, for each adjacent bogie in the wagon sequence.

The two-axle freight wagons from this period cannot achieve the same stress range as the bogie passenger wagons for this structural detail. Although the two-axle wagons have higher axle loads, and four axles can load the structure at any one time, the axles are more spread apart such that the local load intensity is lower compared to the four axles from bogies in the passenger wagons. The freight wagons from this period will also never be able to completely unload the structure, because the longest distance between axles in these wagons is shorter than the influence length of the structure. The maximum stress range from freight traffic will therefore be smaller in magnitude than from passenger traffic for this period.

The number of cycles produced by the different wagon types is obviously linked with the number of wagons in the train, but from fig. 13 we see that each passenger wagon induces one cycle (ignoring boundary effects where only a single bogie loads the structure), while two freight wagons are necessary to load and and one to unload the structure for a cycle. Taking into account that freight trains have more wagons than passenger wagons, one can estimate that the number of cycles introduced in this structural detail for the two train types are rougly equal.

For this particular structural detail and period of rolling stock, the passenger trains will have a larger fatigue damage potential than the freight trains due to the difference in maximum stress range.

Admittedly, the possibility of passenger trains being more damaging than freight trains diminishes for modern trains where the difference in maximum axle load magnitudes are larger, but as a general rule, both passenger and freight traffic should be included in service life assessment due to the difference in axle load magnitudes, geometry, design and operation of these train types and how these parameters influence the response in different structural details.

5.2.3. Changes in dynamic loads on bridges

The total load on the infrastructure from the rolling stock is comprised of a static, quasistatic and a dynamic part. The static loads are calculated with the static axle weights and the quasistatic load is determined by the static weight, speed of the train and geometry of the track. The dynamic loads are due to impact forces at the wheel-rail interface, train-bridge interaction and dynamic characteristics of the rolling stock. The dynamic loads more difficult to calculate than static and quasistatic loads due to mathematical complexity and random nature of the underlying processes. Dynamic loads are therefore typically included in service life assessment by applying a dynamic amplification factor (DAF) to the static loads (Imam & Salter, 2017; Pipinato, Pellegrino, & Modena, 2012a).

The train speed is a common variable for all dynamic effects and the dynamic loads generally increase with train speed. Section 2.5 showed that the train speed has increased over the history of the railways, and one might expect the dynamic forces on the infrastructure to increase as well, but this is not true in general.

Steam locomotives has an additional vertical dynamic force known as 'hammer blow' that is not present in other rolling stock. Hammer blow is a vertical sinusodial force that comes from mass added to the driving wheels to counterbalance moving mass (steam cylinders and connecting rods) in the horisontal direction of the locomotive. Hammer blow was studied in 1920s by the British railways and these studies concluded that hammer blow dominated the dynamic loads on bridges (Hayward, 2014). The American Railway Engineering Association (AREA) also investigated dynamic loads on steel bridges. Their work involved 37 bridges and 1800 diesel/electric and 3400 steam locomotive passages (AREA, 1960), and confirmed that dynamic amplification of stresses in bridges is higher from steam locomotives than other rolling stock. Historic steam locomotives may therefore have larger dynamic loads than modern rolling stock despite running at lower speeds.

The impact forces from the wheel-rail interface is governed by the unsprung mass of the wheelset and the continuity and smoothness of the contact surfaces. The evolution of wheelset mass for the different types of rolling stock has not been established for the Norwegian railway network due to lack of relevant data, but the international literature indicates that reducing the unsprung mass has been of increasing importance to researchers and manufacturers since the 1980s (Iwnicki et al., 2015; Jönsson, 2002). Regardless of the wheelset mass, it is clear that the conditions at the contact surfaces have improved. Historically, rails produced in fixed lengths were joined together by fishplates at the web of the profile, forming a jointed rail (Heie, 1941). The jointed rail surface is discontinous and an impact is produced at the joint for each passing wheel. In 1966, welding was introduced as a joining technique in the Norwegian railway network, and the share of welded rail in the Norwegian railways was 20% in 1970, 60% in 1980 and by 1990 the majority of the railway network consisted of welded rail (Norges Statsbaner, 1953-1996). Welded rail result in a continous rail surface with lower dynamic forces than the jointed track (Esveld, 2001). The discussion above indicates that the impact forces at the wheel-rail interface has been reduced in the last half of the 20th century through reduced unsprung mass and continous welded rails.

In regards to practical applications, there are several sources that propose DAFs for service life assessment of steel railway bridges with respect to fatigue damage, see Imam et al. (2006) for an overview. To specifically include the effect of hammer blow in the service life assessment, the reader might consider AREMA (2008), which presents DAFs for steam locomotives and other rolling stock based on the AREA tests made during the 1950s (AREA, 1960).

5.2.4. Influence of historic loads on the service life estimation of bridges

The load conditions in the Norwegian railway network have generally been characterised by increasing axle loads, train speeds, number of wagons in trains and rolling stock geometry throughout the history of the railway.

For many structural details, this means that historic loads can be ignored due to the increased load conditions of modern traffic. For instance, the structural detail with a short influence length and high sensitivity to axle load magnitude discussed in section 5.2.2 will be dominated by fatigue damage from modern traffic due to higher axle load.

It is however important to note that such an observation does not hold in general. The proportion of fatigue damage that comes from historic traffic compared to more modern traffic will depend on the detail under investigation, the rolling stock and the amount of traffic in each period. The significance of historic loads will therefore vary from case to case.

One aspect of the loading that has not generally increased is the distributed loading on rolling stock. Section 2.1 showed that the distributed loading across buffers was the largest for steam locomotives in service in the middle of the previous century, with section 3.1 confirming that older steam locomotives had a higher local load intensities than more modern locomotives. Considering the static response in the simply supported beam in fig. 13 for instance, several of the steam locomotives has higher maximum stress range than any of the modern electric and diesel locomotives in table 2. It should also be noted that the dynamic loads from steam locomotives are generally larger than for other locomotives, see discussion in section 5.2.3.

Furthermore, the distributed loading on passenger wagons have remained relatively constant over the history of the railways, see section 2.3. Historic passenger trains may therefore be more damaging than modern passenger trains for structural details that are responsive to distributed loading rather than axle load magnitudes, due to the higher distributed and dynamic loading of steam locomotives.

The distributed loading on freight wagons has increased in stages and one might not expect that historic freight trains are more damaging than the modern freight trains, but the stress range induced by the locomotive might mitigate this increase such that historic loads contribute significantly to the fatigue damage.

Since historic loads may have a significant influence on the fatigue damage of railway bridges, and the influence vary from case to case depending on the structural detail, rolling stock and amount of traffic, the historic loads should generally be included in service life estimation of railway bridges.

5.3. Nature of the presented data

The data presented in this paper have been derived from sources that consider the railway domain as a whole. For many of the variables, only the limits on variables affecting the train loading have been presented. When available, the relative frequencies for load conditions are also provided, e.g., the design of locomotives and wagons. Having more information and data will clearly yield more accurate service life estimates of bridge details. Ideally, the distribution of variables defining the load conditions at a bridge should be known so that a probabilistic or rational deterministic analysis can be performed.

The challenge posed by the available data for railway loadings is that we cannot readily link the relative frequency of a variable defined for the rolling stock to the probability distribution of such rolling stock being used at a particular bridge. To illustrate this point, consider the traffic at an arbitrary bridge in the year 2000. Figure 8 shows that among the freight wagons available at the time, approximately 68% were two-axle wagons, 30% bogie wagons and 2% Jacobs bogie wagons. One might assume that the relative frequencies of two-axle, bogie and Jacobs wagons at the bridge follow the distribution of the rolling stock as a whole. It is, however, entirely possible that all freight wagons that pass the bridge are Jacobs bogie wagons. In the year 2000, there were approximately 100 Jacobs bogie wagons available in the rolling stock; four individual trains, each with 25 Jacobs bogie wagons, could be composed using these wagons. The four trains might also be the only freight traffic that pass the bridge, i.e., each train might pass the bridge multiple times a day, depending on the transport distance required by the train. In short, the trains that pass a certain bridge in the railway network are assembled from a subset of the population presented in this paper.

5.3.1. Can the distribution of variables defining the load conditions for a particular bridge be obtained?

In principle, the distribution can be determined if the infrastructure owner and/or operator have recorded and archived the appropriate data for the variable and the bridge. In the case of the Norwegian railway, a tremendous quantity of documentation that *might* contain the information needed to determine the variables' distributions is in fact stored at the railway museums and the national archives. For instance, while research was being performed for this paper, documentation on the exact composition of trains, i.e., the specific locomotive, the set of wagons and the number of trains each day, was obtained for certain bridges and periods. Using such data, it is possible to construct the distribution of locomotive and wagon variables for the particular bridge and period.

Unfortunately, most historic documentation is not easily accessible in the sense of not having been digitised; additionally, a given piece of data is typically not specifically obtained from a single data source, i.e., the data are spread across several documents or even archives. Extracting more precise data than what is already presented in this paper, e.g., determining the distribution of each variable, is therefore resource intensive. Although a substantial quantity of documentation exists that might contain the appropriate data to determine the distribution of a variable, one must also be ready to accept that certain information was never recorded.

It might therefore be possible to obtain the distribution of each variable; however, additional resources will generally be required to do so for each specific bridge.

In conclusion, the data presented in this paper can define the set of possible values of variables for a specific bridge; however, the distribution of the variable over the interval cannot in general be determined. Without the distribution of a variable, the data or information are, from a probabilistic perspective, said to be *imprecise* (Helton & Oberkampf, 2004).

5.4. Use of imprecise data in service life estimation

The service life estimation of a bridge is generally based on a numerical model to predict the response and relevant damage mechanism for the structure. The input variables of such numerical models are all uncertain; service life estimations are based on mathematical frameworks that consider such uncertainty. The way uncertainty is handled is different within each framework and not all frameworks are equally suited for handling imprecise data of the type presented in this paper.

A deterministic analysis generally relies on selecting point estimates for input variables. The point estimates are selected to produce a conservative end result, either by selecting the values directly or by combining nominal values with safety factors. Generally, the probabilistic and non-probabilistic information are treated the same way by selecting the 'worst' values. The deterministic approach does not consider the information available for probabilistic variables and typically leads to conclusions that the detail should have failed a long time ago, i.e., overly conservative results are obtained.

The traditional reliability framework incorporates more information than deterministic point estimate values of a variable and requires that the distributions of variables be known. In comparison to the deterministic approach described above, such an approach leads to more realistic results, with the probability of failure determined by including the uncertainty in the input variables during the analysis. The interval variables presented in this paper cannot be incorporated in the traditional reliability analysis without making assumptions about the distribution of the variables over the intervals.

The framework of imprecise probabilities can incorporate both probabilistic and non-probabilistic information (Beer, Ferson, & Kreinovich, 2013). Imprecise probabilities will therefore be less conservative than a deterministic approach, as probabilistic variables can be handled in a more rational way than simply assuming the worst case. Furthermore, the framework does not require assumptions, as is the case for traditional reliability analysis, since knowledge of the distributions of the variables is not needed.

Imprecise probabilties does not change the fact that available data is imprecise, and does not enable precise determination of the remaining service life of a structure.

From the perspective of bridge owners, imprecise probabilities still have practical advantages in comparison to the established frameworks. In cases were the deterministic analysis proves too conservative, the imprecise probability framework may be applied to show that the structure has sufficient remaining service life since the incorporation of available data leads to less conservative results. Compared to the traditional reliability framework, imprecise probabilities make it easier to communicate the consequence of the imprecise data, since the imprecisions are explicitly expressed in the results of the analysis instead of being expressed through the assumptions made about the data (Aughenbaugh & Paredis, 2006).

The imprecise probability theory has been applied in reliability analysis to problems with imprecise knowledge (Beer et al., 2013; Helton & Oberkampf, 2004); however, there are currently no studies in the literature that apply imprecise probabilities to service life estimation of railway bridges. Demonstrating the use of this framework is outside the scope of the present paper; future work should focus on adapting the methodology to service life estimation of railway bridges due to the nature of available data for such assessments.

In addition to service life estimation, imprecise data can be used in a sensitivity analysis to pinpoint the most important variables affecting the estimated service life. The sensitivity analysis can then be used to identify the variable that should be focused on in further data gathering. A starting point for the sensitivity analysis of imprecise data may be found in Hall (2006); Oberguggenberger, King, and Schmelzer (2009).

In conclusion, the imprecise data presented in this paper can be used in estimating the remaining service life of a bridge by adopting an imprecise probability framework and in a sensitivity analysis to guide further data gathering and assess the possibility of reducing the uncertainty associated with the estimated service life.

5.5. Relevance of findings and discussion to foreign railways

This paper has focused on the evolution of the load conditions and available data for the Norwegian railways. The rolling stock and infrastructure are undoubtedly adapted to Norwegian conditions, with the country's particular topology and climate. Much of the rolling stock has been produced by Norwegian manufacturers, while the infrastructure has been managed and maintained by the Norwegian national railway administration throughout the history of the railways.

It is, however, important to note that the design of the Norwegian rolling stock and infrastructure has been heavily influenced by foreign engineers and practices. For instance, the majority of locomotives have been built by Norwegian manufacturers under licenses from foreign factories, e.g., factories in Sweden, Germany, Switzerland, Britain and the USA (Aspenberg, 2001; Bjerke et al., 1987). Similarly, the railway infrastructure was built or supervised by English and German companies, while the modernisation of the railways was performed while consulting foreign railway experts (Hovestyret for Statsbanene, 1958). International standardisation, e.g., of freight wagons by UIC, as discussed in section 2, and privatisation of the railway infrastructure and operations at the end of the previous century have ensured that the technology of rolling stock and infrastructure were similar across countries during much of the railways' history. A foreign reader may therefore adapt and extend the data presented for the Norwegian conditions by performing a less extensive investigation of available information for railways in another country.

Furthermore, imprecise and missing data for loads in the assessment of the service life of existing structures is a general problem (Melchers, 2001). The need for the simplified equivalent load model (Åkesson, 1994; Sustainable Bridges, 2007) and its use (Pipinato & Modena, 2010), as well as the assumptions made in the development of the British historic load model (Imam et al., 2006; Imam & Salter, 2017), all indicate that information relevant to establishing the distributions of variables for specific bridges is costly to obtain or not available at all for railways outside of Norway.

6. Conclusion

Data on the geometry, design and axle loads of the rolling stock, together with data on the composition and operation of trains throughout the history of the Norwegian railways, have been presented in the initial sections of this paper.

The data show that the maximum axle loads and geometry of locomotives and freight and passenger wagons, as well as train speeds and the number of wagons in trains, have generally increased during the railways' history. Historic loads may however be more damaging than modern traffic for certain structural details. The capacities of both rolling stock and infrastructure influence the load conditions in a railway network. Passenger trains generally differ from freight trains, not only in axle loads but also in geometry, design and operation. As the influence of the geometry, design and operation of passing trains on the response of a structure depends on the specific detail being examined, both passenger traffic and freight traffic over the railways' history should be considered in a service life assessment.

The data for historic railway loads are imprecise, i.e., the probability distribution of variables is generally unknown for a particular bridge. The possibility of obtaining the distribution of variables has been discussed, and although it might be possible to determine the distribution for certain variables and bridges, one must accept that determining the distribution is not possible in the general case. Future work should therefore adapt the mathematical framework of imprecise probabilities to service life estimation of railway bridges to incorporate the available information and improve the accuracy of service life estimates.

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