FATIGUE LOADING AND IMPACT BEHAVIOR OF STEAM LOCOMOTIVES

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ABSTRACT
Steam locomotives were the predominant means of train propulsion for railroads for the 19th century and the first half of the 20th century. The overall size and weight along with dynamic loading behavior created the maximum loading conditions that controlled bridge design specifications. The main design characteristics of concern were the overall weights and the impact characteristics created by the dynamic augment of the counterweighted driving wheels. The dynamic augment is also referred to as hammer blow, and it generated the high impacts that controlled bridge design versus the rolling impact of general equipment. The study of steam locomotives is complicated by the fact that many different arrangements of locomotives were designed with each railroad designing specific details into their locomotive fleets. Actual behavior of these locomotives for weight and dynamic augment is critical because either over- or underestimation of these effects can create serious error in fatigue life estimation. AREA researched and tested bridges in the 1940’s and 1950’s to ensure that design values covered maximum events.

This study examines those actual effects using the data available from previous AREA reports along with use of standardized steam locomotives utilizing the USRA locomotive dimensions developed during World War I. This study includes predictive data for application of steam locomotive impact with comparison to current AREMA(1) recommendations.

INTRODUCTION
From the inception of railroad construction until the middle of the 20th century, power for trains was provided by the steam locomotive in the overwhelming majority of cases. The application of
electric power was not seen on railroads until very late in the 19th century, and the diesel locomotive would not start to be seen beyond prototypes until the late 1930’s and then in passenger use only. Diesel locomotion would not become prevalent on all railroads until after World War II with steam locomotion effectively gone by the late 1950’s.

The steam locomotive provided excellent service and steam locomotive design had reached the point where extremely powerful designs were available at the time they fell out of favor and were retired. One facet of steam locomotive operation that was never completely resolved was the issue of impact on bridges and track due to the action of the rods used to transmit the force from the steam cylinders to the driving wheels. The rods were attached to the driving wheels (called drivers) with an eccentricity to the center of gravity. Although parts of the eccentric weights were balanced, complete balance was never achieved. Due to this imbalance, additional impact force was created from centrifugal and inertial forces. This impact, referred to as dynamic augment, was an important factor in bridge design that had to be included until the demise of steam locomotives. The values used for design impact were considerably larger than the values for impact from rolling equipment that did not have eccentric weights creating a dynamic augment. The effects of the dynamic augment are important in calculations of fatigue life of steel railway bridges. Accurate calculation is also important to avoid either an over- or underestimation of fatigue life that may have been consumed from the passage of steam locomotives over a bridge.

The first development of the modern style of steam locomotive started at the same time that many of the current steel bridges were being built. The modernization of railroads started during the last decade of the 19th century and lasted until World War I. Much of the infrastructure on existing railroads was rebuilt to updated standards and the last thrust for completion of the major portions of the nationwide network were either completed, under construction, or in the planning stages. This modernization encompassed the engineering departments along with the mechanical
departments or the railroads, and resulted in the development of equipment (both locomotives and cars) that set the pattern for railroads that still exists today although there have been increases in train sizes and weights. Many steel bridges built during this time remain in place on those lines still in existence, even if the equipment built at that time has long disappeared. Those bridges have been subjected to a variety of loadings. Although the loadings at the time of construction were lighter than what is in use today, the impact of steam locomotives was greater than the equipment in use today, and the weights of steam locomotives were progressively greater as development progressed.

Understanding of the mechanism of steam locomotive impact is aided by discussing the nature of steam locomotive development and basics of the mechanics that develop the dynamic augment and impact. Additional information on the magnitude of impact is available from testing performed in the 1930’s through the 1950’s. Also included is bending moment data from standardized locomotives developed during World War I which provides data for common locomotives used on nearly all railroads. Finally, this study includes formulation that allows quick calculation of steam locomotive impact.

**Development of the Steam Locomotive**

The steam locomotive was in constant development and change from the earliest construction until the end of its use, and evolution of the form of the locomotive was constant. Technology changes were especially profound during the early portion of the 20th century. Steam locomotives up until that time had generally been larger versions of power that was more reminiscent of post-civil war power. The typical arrangement of steam locomotive power is shown in Figure 1. Larger boilers had allowed additional driving wheels to be added, with increased weight and traffic effort available. The trailing truck had been developed, which allowed even larger boilers and more widespread use of larger driver diameters. This was especially useful for passenger trains, allowing more speed.
Figure 1. Typical Arrangement for Steam Locomotives
After the development of larger boilers, steam superheaters were applied which produced more effective power from the cylinders and more efficient use of the steam produced by the boilers. The other main development in steam locomotive design was the articulated locomotive, combining two engines under one boiler and developing very high tractive efforts for use in heavy drag freight service. These locomotives were useful for either long, heavy trains or were suitable in mountainous regions where gradients caused problems with train resistance forces. The variations of typical steam locomotives are shown in Figure 2.

During World War I, U.S. railroads experienced significant problems moving freight efficiently due to several factors. One of those factors was lack of motive power. During that war, the federal government took control of the railroads under the United States Railroad Administration (USRA) to coordinate freight movement and allocate resources as needed to keep the system operating. To simplify the acquisition of new locomotives, the federal government mandated that standardized locomotive designs be used so that manufacturers could produce locomotives on a faster basis. These locomotives were not ground-breaking in their overall design, but reflected basic designs that provided acceptable performance in various applications.

These locomotives are mentioned because they provide examples of the wheel arrangements that were built and in prevalent use at the time, and bending moment charts can be generated for them that can be used for most any railroad because most railroads had these wheel arrangements (except for the articulateds) and the sizes and weights of these locomotives were similar even between different railroads. The road locomotive arrangements built to USRA specifications were the 2-8-2, 2-10-2, 4-6-2, 4-8-2, 2-6-6-2, and 2-8-8-2. The single-engine locomotives were built in both “light” and “heavy” versions, with the light versions having driver axle loadings of approximately 55,000 pounds and the heavy versions having driver axle loadings of approximately 60,000 pounds. The articulated locomotives were built to the heavy standard for driver axle
Figure 2. Common Steam Locomotive Classifications
loadings. Figures 3 through 5 display the static bending moments for the standard locomotives for span lengths up to 150 feet. The bending moments for the freight and articulated locomotives are assumed with a freight train configuration of 4,000 pounds per foot while the passenger locomotives are paired with a heavyweight passenger train configuration of 2,000 pounds per foot.

During the 1920’s, steam locomotive design and construction again made progress in the last major era for such; the “Super Power” era. The term Super Power was coined by the Lima Locomotive Works for a new style of power developed by them during this period, and this term became generic for all builders during this time. The locomotives provided a lot of variability in design specifications and general features, including larger boilers and new appliances for development of higher steam pressures. Additionally, balance of driving wheels was subject to more intense calculation to improve their rolling characteristics.

Generalization on driver sizes, axle weights, and other overall dimensions is more difficult with Super Power locomotives. With the development of such locomotives, the locomotive design bureaus for each railroad became much more active in developing specialized designs for particular operating requirements and locales. More variety was seen in locomotive sizes, driver diameters, rod configurations, and other items to develop general information on bending moments.

**STEAM LOCOMOTIVE CHARACTERISTICS AND BALANCE ISSUES**

Before the advent of Super Power boilers had been increased with the use of the single-axled (two-wheeled) trailing truck, with boiler pressures in the range of 200 psi. This had been the pattern for new power since the turn of the 20th century. Along with that, driver diameters were in a limited range of 57-63 inches for freight locomotives while passenger locomotives varied from 69-80 inches. These diameters were reflected in the USRA locomotives with essentially the same dimensions (Table 1 (2)). With the introduction of Super Power locomotives, stream pressures increased until a
Figure 3. Static Bending Moments for USRA Standard Freight Locomotives
Figure 4. Static Bending Moments for USRA Standard Passenger Locomotives
Figure 5. Static Bending Moments for USRA Standard Articulated Locomotives
Table 1. Dimensions for USRA Standard Locomotives

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<tr>
<th></th>
<th>2-8-2 Light</th>
<th>2-10 Light</th>
<th>2-8-2 Heavy</th>
<th>2-10 Heavy</th>
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<td>200</td>
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<td>75'11&quot;</td>
<td>82'10&quot;</td>
<td>70'7&quot;</td>
<td>72'6&quot;</td>
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<td>Driver Wheelbase</td>
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<td>Engine Wheelbase</td>
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<td>Total Wheelbase*</td>
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<td>Weight on Engine (kip)</td>
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<tr>
<td>Total Weight (kip)*</td>
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<td>740</td>
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*Total Wheelbase and Total Weight include fuel tender.
maximum of 310 psi was reached. With the higher steam pressures, the cylinder force was increased since cylinder diameters had remained largely unchanged. The larger cylinder force resulted in higher tractive efforts along with the potential for greater speed; both desired effects. An undesired effect that went along with this, however, was increased potential for higher dynamic augment forces due to the need for heavier rods and the higher speeds available from the locomotives.

When Super Power was first introduced, dynamic augment was significant in some instances. Certain early locomotives developed reputations for rail kinks and uplift of the drivers off of the rail under certain circumstances. The problem was solved with three main developments. The first was the use of larger diameter drivers. The original Super Power locomotives were built with 63-inch diameter drivers, which proved too small in most circumstances to allow proper placement of counterweight. The minimum standard driver diameter evolved to 69 inches, usually applied to freight locomotives, with passenger locomotives being designed with drivers up to 84 inches.

The second development that improved the problem of dynamic augment was the development of lightweight rods. Prior to the Super Power locomotives, the chemical composition of rods was typical steel with a normal unit weight. With the requirements of larger rods to handle larger forces, lighter weight alloy steels were utilized which significantly reduced weights of rods. Further development included application of roller bearings to the rods which provided for more even and consistent application of force resulting in more predictable forces.

The third development that was implemented was the process of cross counterbalancing of drivers for portion of the reciprocating weight that was balanced. Cross counterbalancing was used widely in Europe but didn’t gain acceptance in North America until the problems associated with Super Power forced its acceptance. Cross counterbalancing (also referred to as dynamic counterbalancing) took into account out-of-plane forces generated from the other side of the locomotive. The axle between the two sides was effectively a beam, and dynamic augment forces
from one side of the locomotive would be transmitted to the other side. Before Super Power, freight train speeds were generally in the 40 mph range as a maximum, and this portion of dynamic augment was not problematic and was not accounted for. With Super Power, freight train speeds in the 55-60 mph range were easily obtainable and the need for cross counterbalancing became clear.

During World War II, new locomotive production was subject to approval by the War Production Board in the United States. Steam locomotives built during that period were not allowed to be built specifically for passenger operations. As a result, many designs that were originally considered to be passenger locomotives were built as “dual service”, with the result that large passenger power was used in freight service. The use of this power (especially for western railroads) resulted in even higher speeds for freight service, with a potential for some problematic impact. The war restrictions did not allow the use of lightweight rods, but with taller drivers and cross counterbalancing, dynamic augment did not revert to the problems of the pre-Super Power era.

**APPLICATION OF BALANCE THEORY TO STEAM LOCOMOTIVES**

Balancing the engine portion of steam locomotives required the calculation of two separate balancing forces; rotational and longitudinal. The rotational portion of balance was fairly straightforward while the longitudinal forces created the conditions producing dynamic augment.

The parts of the engine with rotational motion were the siderods and crankpins that connected the drivers to each other, the rear portion of the main rod which connected the piston to the drivers, and the parts necessary to transmit the movement of the valve motion (notably the eccentric crank and other levers). Rotational balance was generally achieved at 100 percent, meaning that all of the rotational force that was generated by eccentric parts was balanced.

Longitudinal forces were the more important issue. These forces included those induced by the forward and reverse (reciprocating) motions of the piston and piston rod, the crosshead
assembly, the front portion of the main rod, and associated parts of the valve gear responsible for steam distribution. From 1900 to 1930, general American practice was to assume balancing of the reciprocating weight on each side to 50 percent on that side only. No balancing accommodation for the induced forces from the other side was included. The reason for not balancing to 100 percent is due to how forces are generated in reciprocating fashion. With the cycloidal motion of the main rod, the generated forces change during the revolution of the drivers. Given that the forces change, it is impossible to remain in balance at all times. Attempting to balance at 100 percent would have created the same forces as balancing at 50 percent, but at a different portion of the cycle. No advantage is gained by balancing at 100 percent.

With the increases in speed allowed by Super Power locomotives, the deficiencies in balancing theory became apparent. The 50 percent rule took into account balancing only one side. The forces induced from the other side increased to the point that a deficit in balance for rotating parts became an issue for some locomotives. For some locomotives, the results were that dynamic augment forces were greater than the static weight of the wheel, creating an uplift condition and actually causing lifting of the locomotive from the rail. With this phenomenon in place, cross counterbalance became necessary. The initial effort put forth by the Association of American Railroads was to counterbalance 31.5 percent of the reciprocating weight on the same side while balancing 100 percent of the dynamically generated force from the opposite side. This force was usually the force calculated at diameter speed, the speed in miles per hour equal to the height in inches of the drivers. This was later modified with an increase to 40 percent of the reciprocating weight on each side. The increase was the result of problems with driver slippage when the throttle was opened with higher pressure locomotives. Driver slippage produced high rotational speeds resulting in very high dynamic augment with the consequential track damage and potential
locomotive damage. The additional balance weight helped reduce the slippage and produced better riding locomotives.

From Johnson(3), dynamic augment is calculated by the formula:

\[ F = \frac{1.6047 \times S \times W \times V^2}{D^2} \quad \text{Eq. 1} \]

where:

- \( F \) = centrifugal force (dynamic augment), pounds
- \( S \) = stroke of the piston, inches
- \( W \) = weight of the reciprocating counterbalance, pounds
- \( V \) = speed of the locomotive, miles per hour
- \( D \) = driver diameter, inches

This formula is a derivation of the general equation for calculation of centrifugal force. As such, it is simple to comprehend that the force increases exponentially with the speed, while driver diameter and the counterbalance weight can be utilized to lower the induced force. Conversion to impact is accomplished by dividing the calculated dynamic augment by the static weight on the driver. Driver diameter played a big role in reducing the dynamic augment, so it played an important part in not only reducing the that force, but being sized to provide sufficient space to place counterweight in an efficient manner.

From a present-day perspective, being able to accurately calculate this formula is somewhat daunting, because the biggest deficiency in available information is knowledge of the amount of reciprocating counterweight that has been applied to a given locomotive. The other required dimensions can be obtained from various locations, ranging from trade publications to historical and
special interest publications. Counterweight is not an area where many records have been preserved. General guidelines are available, however, and can be applied to a degree. Several different parameters are available from various publications, which can give varying results. Specific data on reciprocating balance weight is available from various AREA reports from testing (4-8). Results from that indicate for most locomotives, reciprocating counterweight is in the range of 200-250 pounds per driver. Locomotives built with lightweight rods can have values less than that, and certainly there were others built with more reciprocating balance weight than that, but the suggested range provides an acceptable starting point for any calculations.

**EVALUATION AND ANALYSIS OF TEST DATA**

Precise calculation of dynamic augment and impact may not be necessary in all instances, and data from a series of AREA tests is available that provides estimation of not only the dynamic augment but is inclusive of all impact factors. The testing, all on girder spans of various types, was summarized (9) and the data was used to develop equations that can simply estimate an average value of impact including dynamic augment.

The data in the summary report included span length and an average of the six highest impact magnitudes for each bridge for both steam and diesel locomotives experienced during the testing. The locomotives included a variety of steam and diesel models as well as different types of spans, so general conditions were assured. This is in congruence with design impact equations where no specific information is required other than the type of impact (either rolling or hammer blow) and span length for either girders or trusses. From the available data, two different equations are available for estimating actual total impact from steam locomotives. One formula accounts for velocity while the other relies strictly on span length.
From the maximum impact data available from the testing, the maximum actual total impact from steam locomotives can be estimated from the formula:

\[ I = (50 - 0.2L) \times \frac{V}{100} \]  \hspace{1cm} \text{Eq. 2}

where:

\[ I \] = impact (percent)

\[ L \] = span length (feet)

\[ V \] = velocity (miles per hour)

Using standard linear regression, average actual total impact from steam locomotives can be estimated from the formula:

\[ I = 39 - 0.18L \]  \hspace{1cm} \text{Eq. 3}

where:

\[ I \] = impact (percent)

\[ L \] = span length (feet)

Figure 6 displays the results of the equations versus the data points for the average maximum steam locomotive impact from the summary report. Equation 2 is plotted based on maximum impact at full velocity. The use of Equation 2 generates values that are obviously in excess of most test data. Given that the purpose of the estimation is for use in fatigue and overall load rating, the use of that equation may lead to values that are inappropriately high.
Figure 6. Estimation of Steam Locomotive Impact
Also displayed in Figure 6 is the AREMA impact equation for steam locomotives adjusted for fatigue analysis using 35 percent of the design value as allowed in Table 15-1-8 of AREMA Chapter 15, Article 1.3.13. Equation 3 provides impact values that are comparable with the AREMA impact equation as well as providing good correlation with the data. A check can be made to see if the assumption of 35 percent for steam locomotive data is appropriate when evaluating the proposed equation.

In conjunction with steam locomotive testing, diesel locomotive impacts were measured in the same manner. From linear regression of the diesel data from the summary testing, the average maximum total impact for diesel locomotives can be calculated from the formula:

\[
I = 29 - 0.135L
\]

Eq. 4

where:

\[
I = \text{impact (percent)}
\]

\[
L = \text{span length (feet)}
\]

The results of the equation are displayed in Figure 7, along with the data and the AREMA diesel impact equation at the 35 percent level used for fatigue design. The figure clearly demonstrates the same relationship for the linear regression equation when compared to the AREMA equation.

The difference between the two equations 3 and 4 can be equated to the expected dynamic augment force created by steam locomotives. While dynamic augment is theoretically calculated as a function of speed, for this data set the difference between the total steam locomotive impact and the
Figure 7. Estimation of Diesel Locomotive Impact
diesel locomotive impact is based on the average maximum measured impact by span length. This
gives us a measure of the effect of span length on dynamic augment. Taking the difference between
the two equations, dynamic augment on any girder span length can be estimated by the formula:

\[
DA = 10 - 0.045L
\]

\textbf{Eq. 5}

where:

\[
DA = \text{dynamic augment (percent)}
\]

\[
L = \text{span length (feet)}
\]

\textbf{SUMMARY}

Issues with dynamic augment were always challenging when attempting to quantify steam
locomotive impact. Calculation based on using the available test data provides a simple method to
provide a value for the dynamic augment. The data used on this analysis was broad-based in the
variety of locomotives employed along with the types of girder spans used in the testing. While the
theoretical equation for dynamic augment can be used in these instances, availability of appropriate
data is somewhat limited.

Additionally, calculated values of dynamic augment do not always translate into the actual
impact experienced by a bridge. Track irregularities and other conditions beyond the locomotive
create the atmosphere for additional impact. The availability of test data allowed for approximation
equations that reflect actual experience which takes into account the damping effects of the bridge,
track effects and support, and other items which make actual values differ from the theoretical.

The new equations provided in this study allow for quick calculation of total impact for
either steam or diesel locomotive powered trains on girder spans for use in fatigue analysis or load
rating. These equations provide a check or alternative to the AREMA equations for use as needed.
REFERENCES


List of Figures

Figure 1. Typical Arrangement for Steam Locomotives
Figure 2. Common Steam Locomotive Classifications
Figure 3. Static Bending Moments for USRA Standard Freight Locomotives
Figure 4. Static Bending Moments for USRA Standard Passenger Locomotives
Figure 5. Static Bending Moments for USRA Standard Articulated Locomotives
Figure 6. Estimation of Steam Locomotive Impact
Figure 7. Estimation of Diesel Locomotive Impact

List of Tables

Table 1. Dimensions for USRA Standard Locomotives