Development of Rail Gage Face Angle Standards to Prevent Wheel Climb Derailments

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Introduction

Rail represents that part of the track structure that first "meets" the wheel and thus directly carries the wheel/rail loading imposed by the traffic operating over that track. As such it is subject to a significant level of dynamic loading; vertical, lateral, and longitudinal, and it must support these loads safely and economically. This requires an adequate level of strength of the rail, together with a proper support capability of the wheels.

Traditional rail standards, and in particular rail wear standards, are generally strength based, so as to insure that the rail can adequately support this traffic without failure, e.g. fracture under traffic. By combining strength based wear standards with ongoing monitoring of fatigue failures (fatigue standards), railway maintenance officers define a zone of safety for the rail, beyond which the rail must be removed from track.

In addition, rail represents a major cost area in the maintenance of the track structure, representing, for main line freight railroads, as much as 50% of the total variable cost of track maintenance. Thus, the decision as to when and where to replace the rail is an important one, not only from the point of view of safety, but also from the point of view of cost and economics. Leaving rail in track for too long can result in a service failure and the potential for a derailment. Removing a rail prematurely translates into significant costs for the railway. Thus maintenance officers must maintain a proper balance between safety and cost control. In the case of rail, this is done through the use of cost effective standards for the rail that maintains an adequate margin of safety for the track structure.

To add to the complexity of maintaining these adequate standards, evolving operating conditions and maintenance practices have resulted in significant changes in the way railways determine when rail should be replaced in track. These changes stem directly from changes in maintenance of way practices and materials that have occurred during the past two decades, i.e. better higher strength rail, cleaner steel, improved lubrication and grinding practices, etc. as well as from changes in operating practices, i.e. heavier trains, increased axle loads, higher operating speeds, etc. The net result of these changing practices has been the extension of the service life of the rail, and often an overall reduction in rail maintenance costs over that life [1]. Thus, for example, the decreasing importance of rail joints, and the dramatic extensions of rail life through the use of effective lubrication, grinding, and improved steels [2]. While increasing axle loads have resulted in an increased emphasis of fatigue defects, rail wear remains a key replacement criterion for all rail systems to include freight, passenger, and transit systems. Thus, the importance of maintaining appropriate and adequate rail wear standards likewise remains.

Recently, increased attention has been paid to the wheel/rail dynamic environment of the track structure, with major emphasis placed on the shape of the wheel and the rail [3]. This has led to a better understanding of several classes of derailments, to include those wheel climb derailments associated with excessive wear of the rail and/or the wheel [4]. This has become of even greater importance in recent years, as several classes of derailments have been associated with these levels of wear. It is the focus of this paper to examine those conditions, and to identify those rail wear criterion and standards that can reduce the potential for occurrence of these classes of wheel climb derailments.

Traditional Rail Wear Standards

Traditional rail standards for the determination of the replacement point for rail in track include wear standards, fatigue (internal) defect standards, surface defect standards, and joint standards. Of these standards, rail wear standards are generally well defined and codified for main line and secondary tracks, with most rail systems (freight, passenger, and transit) having defined wear standard tables in their maintenance of way standards books. This reflects the railways concern about. the maintenance of the strength of the rail section, and the corresponding loss of strength due to rail wear.

Rail wear, in turn, is generally divided into two broad categories corresponding to its locations on the rail head. These two categories of rail are:

Head wear or wear on the top running surface of the rail ("h", see Figure 1).

> This wear is most commonly associated with tangent and shallow curves where the wheel/rail contact is exclusively on the head of the rail. Head wear will also occur on curves, to include severe curves, however, in that environment side or gage face wear will usually dominate.

Side or gage face wear, i.e. wear on the side of the rail head ("g", see Figure 1).

> This wear is caused by contact of the side of the rail head with the flanges of the wheel, and is associated with moderate to severe curves. Note that flanging generally takes place on curves 3 degrees and greater, although flanging can occur in shallow curves and even on tangent track (due to hunting).

Gage face wear is usually measured 5/8" below the top of the rail head (the gage point of the rail [5,6]). Thus, its exact location is dependent on the degree of vertical head wear. Gage face wear also results in a loss of rail section strength (vertical) as well as the lateral bending strength of the rail head. When this loss of strength is sufficient to permit the development of stress levels greater than the allowable stress limits (under Lateral as well as Vertical loading) then the rail should be replaced (wear limit).

Gage face wear is also a relatively easy parameter to measure, with both manual and automated methods of measurement commonly used.

c. Linear combinations of head and side wear

In order to account for combined head wear and gage face wear, a linear combination of the two wears (h + g) can be used to establish limits. This allows for the reduction in head metal, and thus rail bending strength, associated with both head and gage face wear. However, it requires the combining of two independent measurements into a "surrogate" measure that, by itself does not have a physical meaning. It also requires different standards for high and low rails, since the relationships between head and gage wear is significantly different for these two rails.

While this parameter is relatively easy to measure with both manual and automated techniques (since it is simply a linear combination of the above two measurements), this approach has been used only on a limited basis by one or two railroads and no transit systems, due to the difficulty in defining meaningful values.

d. Allowable head area loss (as percent of head area)

A more accurate method of accounting for combined gage face and head wear is through the calculation of the area loss of metal, and specifically the loss of head area. This value, referred to as head area loss, is usually given in the form of a percentage (%) of the head area that has been worn away.

While this is a more accurate way of determining total wear and the corresponding loss of rail bending strength, this parameter can not be readily obtained in the field with any standard measuring tool. It requires a detailed rail head profile, such as would be obtained by a profile measurement system (as mounted on an inspection vehicle) and a follow up area analysis. With the increased use of automated optical rail wear measurement systems, this parameter can be more readily obtained and thus has the potential for increased usage in defining rail wear limits. Too date, however, most rail systems standards do not account for this parameter.

The corresponding limits or standards for these wear parameters are generally based on the bending strength of the worn rail section (though historically vertical wear has also been defined by the need to avoid wheel flange contact on the top of the joint bars). In order to permit adequate definition of these standards, permissible rail wear limits have been defined in several interrelated ways, as illustrated in Figure 1. These include:

a. Allowable vertical head loss (h)
b. Allowable side (gage face) head loss (g)
c. Linear combinations of head and side wear
d. Allowable head area loss (as percent of head area)

Traditionally, North American rail systems have used the first two limits, head and side wear, because of their ease in measurement and relative simplicity of application.

a. Allowable vertical head loss (h)

Vertical head loss refers to the loss of metal from the top surface of the rail head, as illustrated by parameter "h" in Figure 1. As noted above, vertical head loss occurs on all track, but is a dominant mode of wear on tangents and shallow curves.

Vertical head wear results in a direct loss of rail section strength, since the moment of inertia of the rail section (and thus its bending strength) is related to the rail section height raised to the fourth power. Thus head wear translates directly into a loss of rail bending strength and a corresponding increase in rail bending stresses. When these stresses are greater than the allowable rail stress, then the rail should be replaced for wear (rail wear limit).

Vertical head loss, as defined here, is measured independent of any other parameter, and is taken at the center of the rail head. Vertical head loss is a relatively easy parameter to measure. Both manual and automated methods of measurement are commonly used.

b. Allowable side (gage face) head loss (g)

Gage face wear or side head loss refers to the loss of metal from the inside or gage side of the rail head, as illustrated by parameter "g" in Figure 1. Gage face wear occurs primarily on curved track when flanging of the wheels occurs. It is most pronounced and dominant for curves greater than 3 to 4 degrees. However, it can also be found on tangents and shallow curves, particularly when hunting or truck skewing occurs.

The above wear parameters represent the "traditional" parameters used by rail systems to define their limits. As already noted, they are all strength based, derived from the bending strength of the rail (primarily in the vertical orientation, but also in the lateral orientation). Thus, they are all aimed at determining whether the rail section has adequate strength to support the traffic loading, to include dynamic impact loads that have been measured to be three or more times the static wheel load [7]. Their intent, is therefore, to insure that the rail does not break under traffic.

Recent research, however, has indicated that wear affects not only the strength of the rail, but also the dynamic interaction between the wheel and the rail. This, in turn, influences not only the wheel/rail loading environment [3], but also the potential for dynamic wheel climb and its associated modes of derailment [4]. Thus, it becomes necessary to extend the wheel wear standards beyond these traditional strength based standards, and to address the wheel climb potential associated with the wear of the rail head.

Wheel Climb Derailments and Gage Face Wear Angle

Dynamic wheel climb is a class of derailments most commonly associated with high levels of lateral loads and corresponding high L/V ratios (ratio of Lateral wheel/rail force to Vertical wheel/rail force). Dynamic wheel climb has been reported for all modes of rail operations to include freight, passenger, and transit operations. Significant research has been directed towards the mechanisms associated with dynamic wheel climb derailments with derailment criterion developed by such researchers as Nadal, Weinstock, and others [8].

Dynamic wheel climb derailments are most commonly associated with sharp curves, where high levels of lateral wheel/rail force are generated. Similarly, wheel climb derailments are found on turnouts, particularly in the curved portion of the turnouts, again where high levels of lateral wheel rail forces have been developed. One survey of turnout related derailments in transit systems (to include both main line and yard derailments) has found approximately 40 reported wheel climb related derailments, which corresponds to more than 40 % of all turnout related derailments (track caused) reported in that study.

Among those factors that have been reported to contribute to this class of wheel climb derailments is the angle of the gage face of the rail, usually the outside or high rail of the curve. This angle is often found on rails subject to gage face wear, i.e. outside or high rails, where this gage face wear can result in the development of an angle ϕ between the gage face and the vertical (see Figure 1). As this angle increases, the potential for a wheel to climb the gage face of the rail increases. This wheel climb will occur when the net "upward" component of the lateral (L) and vertical (V) wheel/rail forces, parallel to the rail gage face, is greater than the resistance to that force due to the normal force component N (see Figure 2) and the corresponding coefficient of friction f, i.e. $N \bullet f$ [9,10]. Thus wheel climb can occur when the following relationship occurs (see Figure 3):

$$L/V < \tan(\beta - f') \quad \{1\}$$

where:

L = Lateral wheel/rail force

V = Vertical wheel/rail force

$\beta = 90 - \phi$ (see Figure 3)

$f' = \tan^{-1}(f)$

and

f = coefficient of friction

Thus, based on the above equation, as the gage face wear angle ϕ increases, the corresponding level of LN ratio required for wheel climb decreases, thus increasing the risk of wheel climb derailments. In order to reduce this risk, some rail properties have introduced a standard for the maximum angle of side wear of the rail. This criterion has been introduced recently on several US rail systems, in some cases shortly after investigation of a wheel climb derailment found that this wear angle was a contributing factor. This was the case recently on BART (San Francisco) and PATCO (New Jersey). This criterion has also been extensively used in Europe and Asia, where rail gage face angle limits have been used on such rail systems as British Rail [11], Deutche Bundesbahn [12], Indian Railways [13], and the Netherland State railways [9]. This criterion has recently been adopted by a number of US rail systems to include Amtrak, and several US transit systems, as a supplemental safety standard to their rail wear standards.

Until recently, measurement of this gage face angle had been difficult to accomplish, usually requiring special gages which have been developed by individual properties. However, with the growing use of optical rail wear measurement systems which define a complete rail head profile accurately and reliably [14], it is possible to calculate this rail gage face angle value directly from the measured rail head profile. This is, in fact, the approach that has been introduced by Amtrak, as part of its ongoing rail wear inspection program using a contracted optical wear measurement system. By defining an algorithm for the calculation of gage face wear angles, as part of the analysis of the rail profile data, and comparing these angles to preset thresholds, exception reports are obtained from those locations where the rail gage face angle values exceed these thresholds.

It should be noted that the actual values used for these standards vary, based on the expected levels of L/V ratio for the operating equipment and operating conditions. Thus, limits for wheel climb that have been used by different properties vary from between 26 degrees and 32 degrees, depending on level of expected L/V ratios, and desired margin of safeties. This will be discussed in further detail in the next sections.

Wheel Climb Sensitivities

As can be observed in Figure 3, the wheel/rail forces normal and parallel to the gage face (and thus associated with this risk of wheel climb) are functions of the lateral (L) and vertical (V) force values, and their corresponding ratio (the LN ratio). They are also sensitive to the angle of gage face wear <1>, and the coefficient of friction (f) (see equation {I}). Since the potential for wheel climb is directly related to the LN ratio, it is possible to define those combinations of LN ratio, gage face wear angle (ϕ), and coefficient of friction (t), which introduce an unacceptable level of risk for wheel climb.

Figures 4 through 9 present such a sensitivity analysis, which shows the calculated L/V ratios associated with wheel climb as a function of different gage face angles and coefficients of frictions. As can be seen from Figures 4 and 5, increased levels of friction, corresponding to dry or unlubricated rail, reduce the L/V ratio required for wheel climb at a given gage face angle, thus increasing the potential for wheel climb by bringing the level of loading required down to a magnitude where this level of loading has in fact been measured. While normal lubricated rail has a range of friction of the order of 0.10 to 0.35, depending on level of lubrication, dry or unlubricated rail can have a coefficient of friction of the order of 0.45 or higher (with values as high as 0.6) [15]. Thus, effective lubrication not only has the ability of reducing the level of lateral loading [16], but also increases the level of loading needed for wheel climb to occur, even at high gage face wear angles. Conversely, dry or unlubricated rail can directly increase the risk of wheel climb derailments. In fact, in several of the derailments noted above (i.e. PATCO, BART), the gage face of the rail was very dry at the time of the derailment, thus contributing to the derailment itself.

To illustrate this behavior, for a well lubricated condition, with a coefficient of friction of 0.2 and a gage face wear angle of 28 degrees, the level of L/V required for wheel climb is 1.20, a very high level rarely seen in service. However, for a very dry condition, corresponding to a coefficient of friction of 0.5, the same amount of gage face wear angle results in a L/V level required for wheel climb of 0.70. This is a level that has been measured in the field on a regular basis, and is, in fact, below the traditional Nadal wheel climb threshold of 0.8.

Likewise, increasing the allowable gage face angle, i.e. allowing a steeper "slope" at the gage face, while holding coefficient of friction constant (see Figures 6 through 9) will result in a reduction in the L/V ratio required for wheel climb and consequently increasing the potential derailment risk. Thus, as can be seen in Figure 7 (for a coefficient of friction of 0.4), a gage face angle of 18 degrees requires an L/V ratio of 1.20 for wheel climb, an extremely high level which is almost never achieved, while a gage face angle of 32 degrees requires an L/V ratio of 0.7. As noted above, this is a value which has been measured in the field for a range of vehicle types and operating conditions.

It can thus be seen that by setting a maximum limit to the gage face wear angle, it is possible to reduce the risk of wheel climb, by forcing the wheel climb requirements to a level of loading (L/V ratio) that will not be encountered in the field. Alternately, if the maximum L/V ratio that occurs on track is known (through field measurements, tests, analytical modeling, etc.), together with an appropriate coefficient of friction, then it is possible to calculate the maximum allowable gage face angle above which wheel climb may occur. This would thus be the limit for maximum allowable gage face wear angle.

Recent Experience and Practice

As noted above, gage face wear angles limits can be used to control the risk of this class of wheel climb derailments. These limits can be defined most effectively, if the actual levels of Lateral (L) and Vertical (V) loadings are known, thus defining the range of L/V values for the system. This approach was used by such properties as Amtrak and PATCO in setting their gage face wear angle standards. In both cases, test data was available which defined the range of loadings and L/V ratios expected in service. Using these L/V ratio limits, and knowing the lubrication practices, and thus, expected coefficients of friction, it was possible to define maximum allowable gage face wear angles so as to avoid wheel climb.

For example, in the case of PATCO, maximum measured lateral load values (L) were available from previous field tests. Using the worst case measured lateral load levels, combined with the lightest vertical loads (usually unloaded equipment), it was determined that the L/V ratio for this equipment was always less than 0.84 for unguarded curves (no guard rail). Defining a light to moderate level of lubrication (0.4), results in a gage face wear angle limit of 0.28 degrees. Noting that drier rail (higher coefficient of friction) will reduce this angle limit (see Figure 7), a gage face limit standard of 26 degrees was defined.

Amtrak likewise made use of available loading and L/V data to define a gage wear angle limit of 30 degrees (based on a defined set of operating conditions, corresponding to that level of loading). Amtrak furthermore made use of its contract rail profile measuring activity to inspect for this wear angle and is currently experimenting with the threshold limit for use in the generation of "exception" reports to define locations with excessive gauge face wear angle values. Currently a "maintenance" limit of 27 degrees is being used to define exception locations.

Other US properties, to include BART (San Francisco), PAT (Pittsburgh) and SEPTA (Philadelphia) have defined gage face wear limit values between 26° and 32°, based on the anticipated (or measured) levels of loading, and standards for lubrication.

While most freight systems in North America have not adopted gage face wear standards, as of yet, their European counterparts have. In Europe, where this parameter is frequently used, standards likewise range from 26 degrees to 32 degrees.

Thus, for example, British Rail uses a gage face wear angle standard of 26 degrees [II], defined as illustrated in Figure 10 (note this angle corresponds to angle ϕ in Figure 1). As noted in Reference 11, this limit is imposed to avoid derailments, i.e. to prevent the class of wheel climb derailments already noted above.

Other European and international railways, likewise use a gage face wear angle limit or alternately, use a more restrictive limit to measure gage face wear, in lieu of the angle limit, in order to restrict wear and prevent excessive gage face wear angle values. Thus, for exan1ple, on the NS (Netherlands Railways), the limit for lateral (gage face) wear is 8 mm (.32 inches) without any gage face angle limit, or it is extended to 12 mm (0.5 inches) if a gage face angel limit of 32° is imposed [9]. Likewise Indian Railways define limits of lateral wear and angle of wear to avoid the "risk of wheel mounting the rail caused derailments" [13].

Finally, the issue of measurement of this gage face wear angle value should be addressed. While several rail systems have developed hand gauges which can be used to measure gage face wear angle (e.g. BART, PATCO), either as a direct measurement or as a go/no go gauge, current rail profile measurement technology now allows for the measurement of the complete rail section. This approach, most commonly using optical techniques which have been used by numerous rail systems both in North America and overseas, readily lends itself to the calculation of this gauge face angle. This is the approach currently used by Amtrak, where by defining a "zone" on the gage face of the rail, the actual wear angle is calculated and compared to the defined standard (be it a safety or maintenance standard). Exception locations can then be identified, and if desired, an ongoing record of condition maintained. This approach is expected to be used more and more in the future, since it can be readily incorporated into current rail wear measurement practices with the incorporation of an additional calculated parameter.

Summary

Traditional rail standards, and in particular rail wear standards, are generally strength based, so as to insure that the rail can adequately support traffic without failure. In this approach a zone of safety is defined beyond which the rail must be removed from track. In addition, rail represents a major cost area in the maintenance of the track structure. Thus, the decision as to when and where to replace the rail is an important one, not only from the point of view of safety, but also from the point of view of cost and economics. As axle loads increase and operating conditions become more severe, the importance of maintaining safe and appropriate rail wear standards becomes of even greater importance to cost conscious railroads.

As railroads' understanding of the wheel/rail dynamic environment of the track structure increases, a better understanding of several classes of derailments, to include those wheel climb derailments associated with excessive wear of the rail, has emerged. These dynamic wheel climb derailments are a class of derailments most commonly associated with high levels of lateral loads and corresponding high L/V ratios. Dynamic wheel climb has been reported for all modes of rail operations to include freight, passenger, and transit operations.

Among those factors that have been reported to contribute to this class of wheel climb derailments is the angle of the gage face of the rail, usually the outside or high rail of the curve or in a turnout. As this angle increases, the potential for a wheel to climb the gage face of the rail increases. This wheel climb will occur when the net "upward" component of the lateral and vertical wheel/rail forces, parallel to the rail gage face, is greater than the resistance to that force.

By defining standards or limits for these gage face wear angles, the risk of this class of wheel climb derailments can be controlled. This approach has been used by numerous rail systems both in North America and overseas to reduce derailment risk for this class of derailments. In the case of several US properties, test data which defined the range of loadings and L/V ratios expected in service was used, together with lubrication condition (which defined the coefficient of friction between the wheel and the rail) to define maximum allowable gage face wear angles so as to avoid wheel climb.

In the US, several properties have defined gage face wear limit values between 26° and 32°, based on the anticipated (or measured) levels of loading, and standards for lubrication. Likewise, in Europe, where this parameter is frequently used, standards similarly range from 26 degrees to 32 degrees.

In order to measure these angles, several rail systems have developed hand gauges which can be used to measure gage face wear angle, either as a direct measurement or as a go/no go gauge. However, current optical rail profile measurement technology allows for the measurement of the complete rail section, and thus readily lend itself to the calculation of this gauge face angle. This is the approach currently used by at least one US property to calculate the rail wear angle and compare it to a defined standard (either safety or maintenance standard). This approach is expected to be used more and more in the future, since it is readily incorporated into the current rail wear measurement practices.

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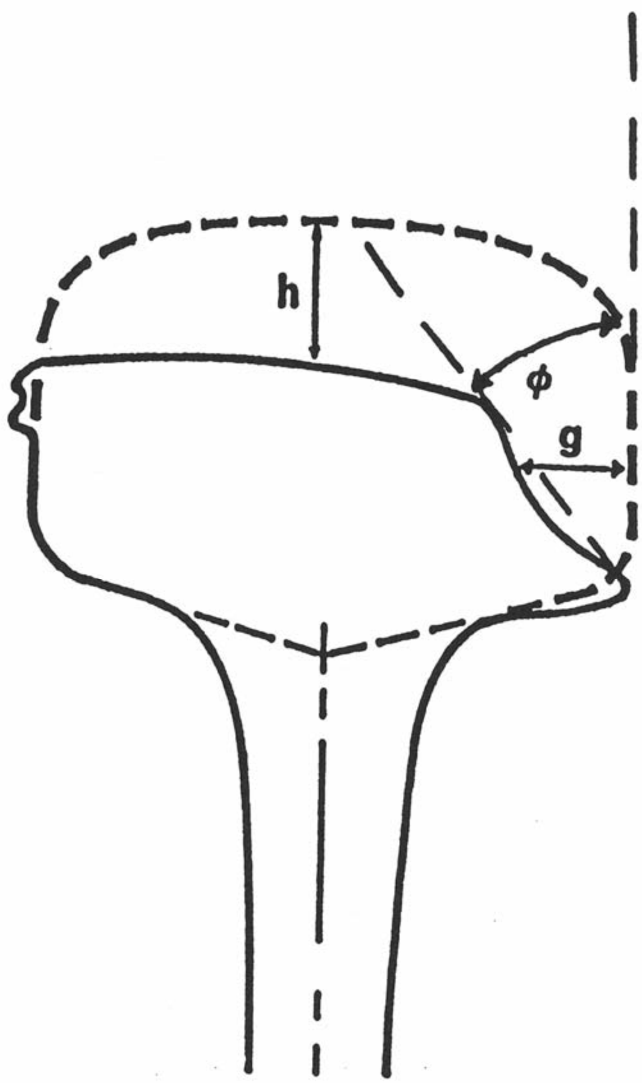


Figure 1: Rail Wear Criterion

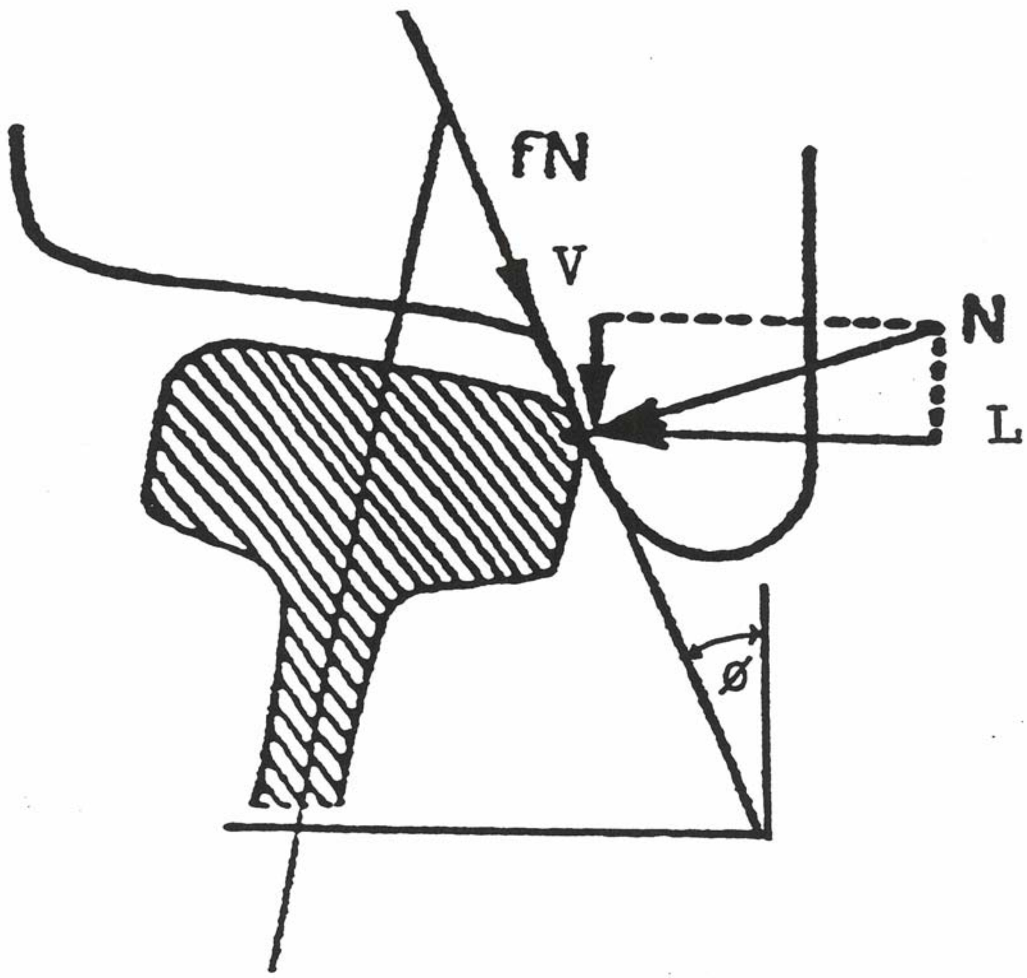


Figure 2: Wheel Climb Potential

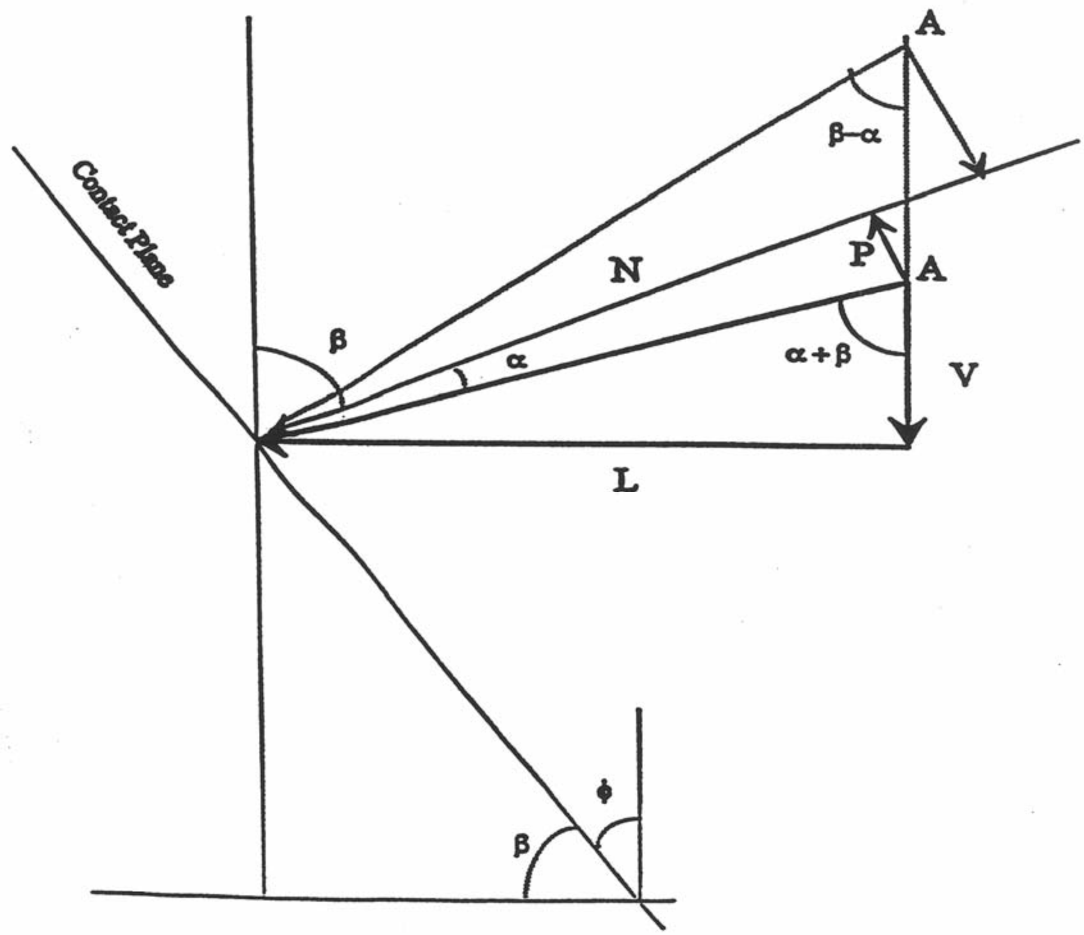


Figure 3: Wheel Climb Force Diagram

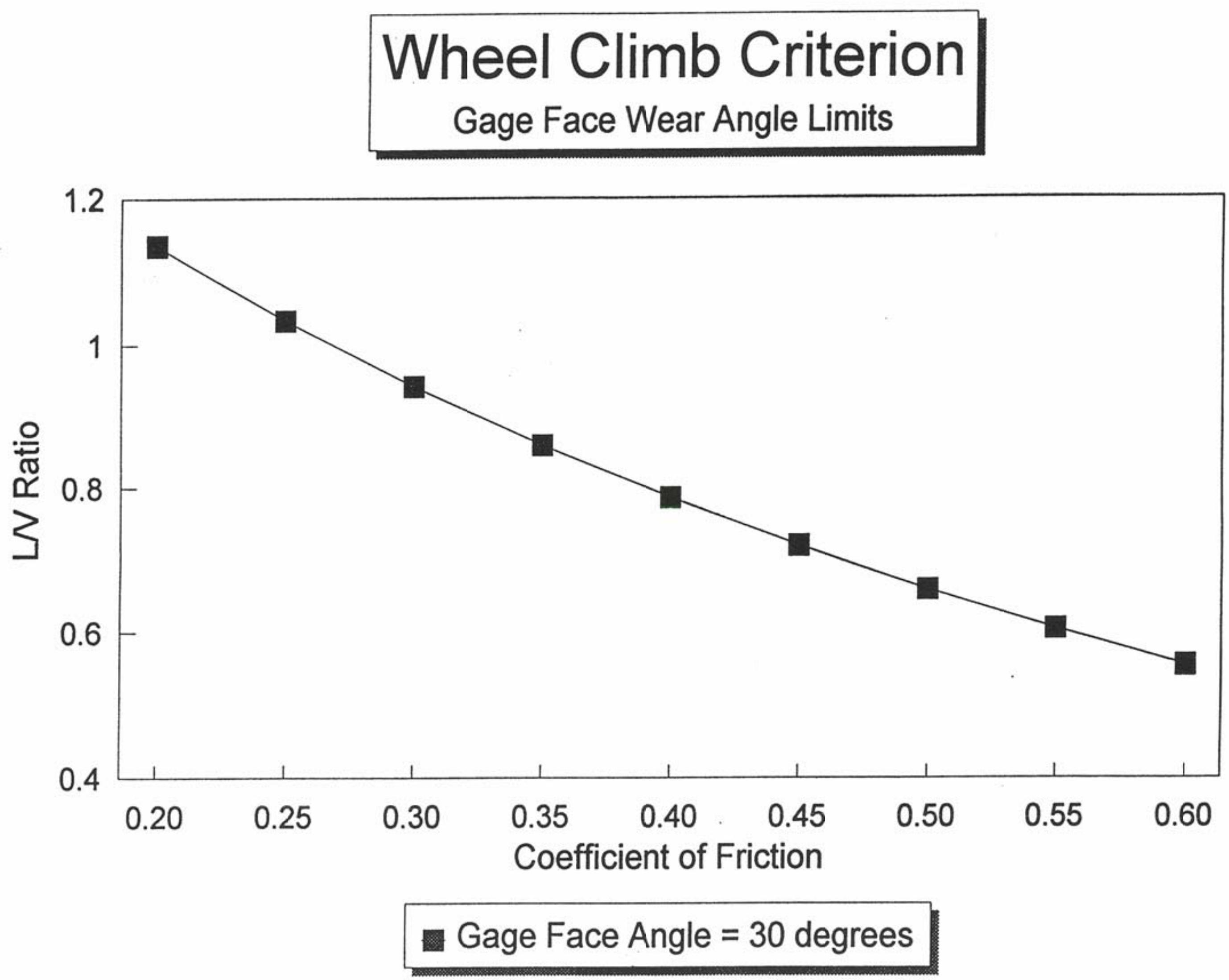
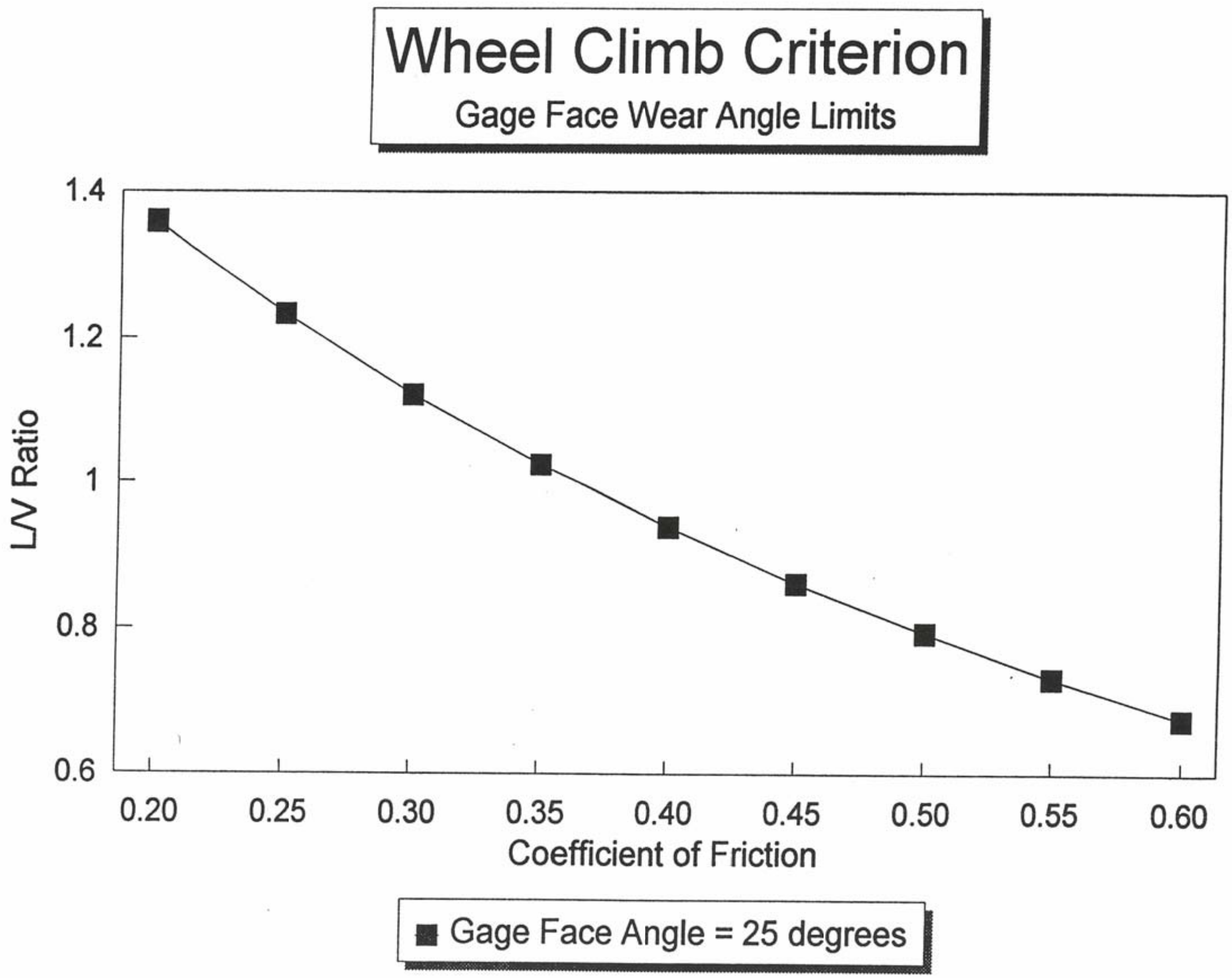

Wheel Climb Criterion
Gage Face Wear Angle Limits
L/V Ratio
1.2
1
0.8
0.6
0.4
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Coefficient of Friction
Gage Face Angle = 30 degrees

Figure 4



Wheel Climb Criterion
Gage Face Wear Angle Limits
L/V Ratio
1.4
1.2
1
0.8
0.6
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Coefficient of Friction
Gage Face Angle = 25 degrees

Figure 5

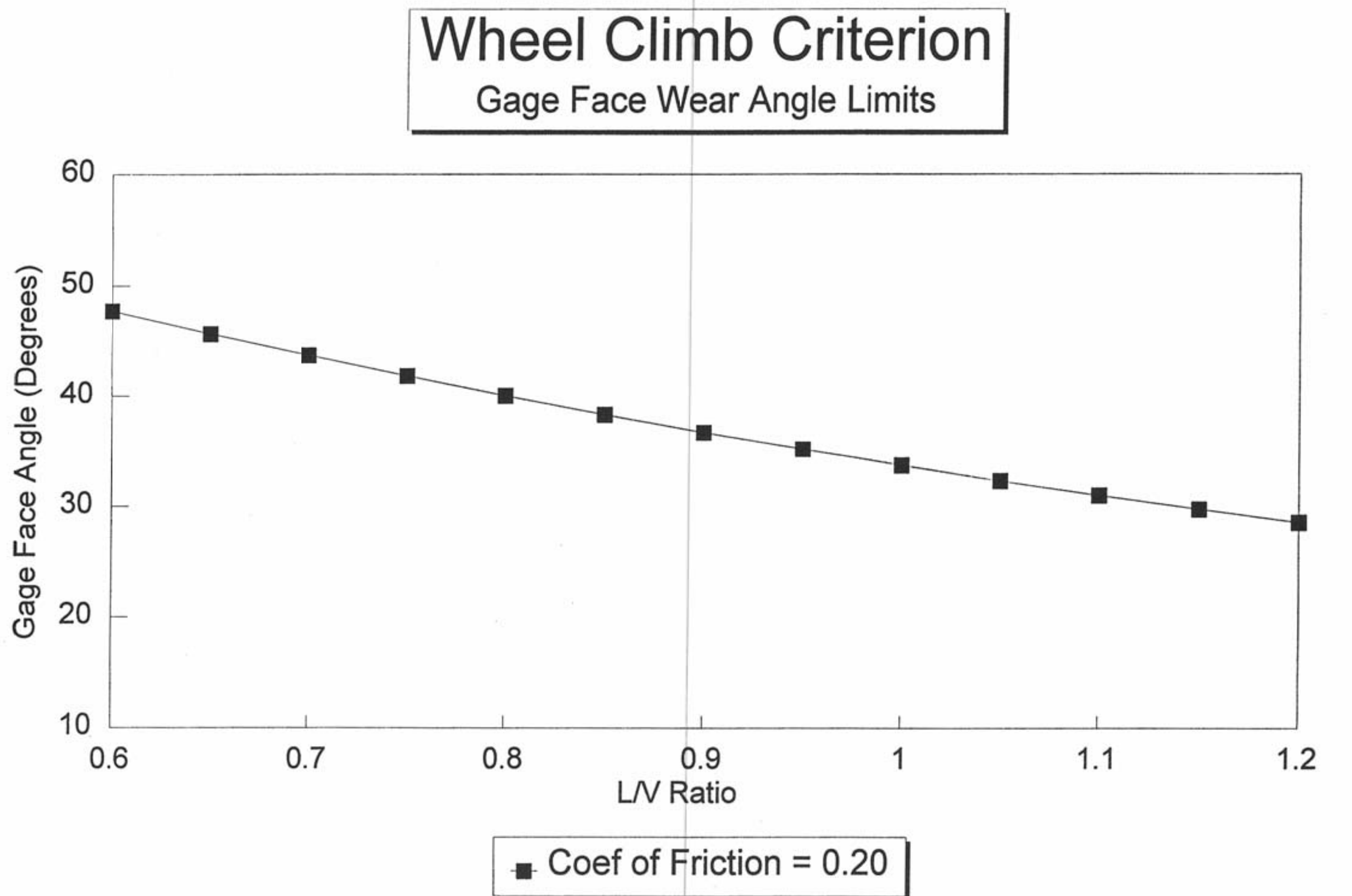

Wheel Climb Criterion
Gage Face Wear Angle Limits
Gage Face Angle (Degrees)
60
50
40
30
20
10
0.6
0.7
0.8
0.9
1
1.1
1.2
L/V Ratio
Coef of Friction = 0.20

Figure 6

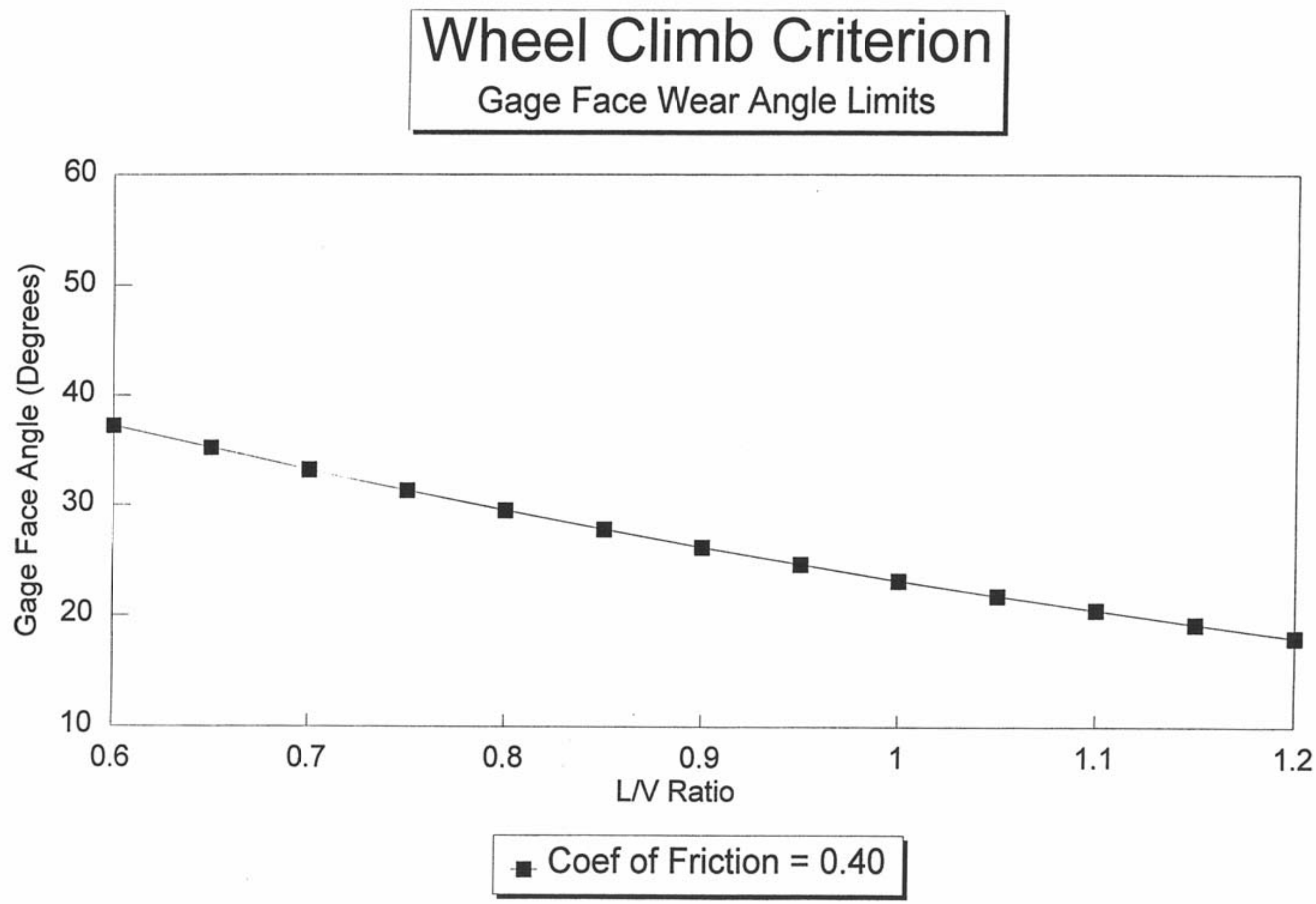

Wheel Climb Criterion
Gage Face Wear Angle Limits
Gage Face Angle (Degrees)
60
50
40
30
20
10
0.6
0.7
0.8
0.9
1
1.1
1.2
L/V Ratio
Coef of Friction = 0.40

Figure 7

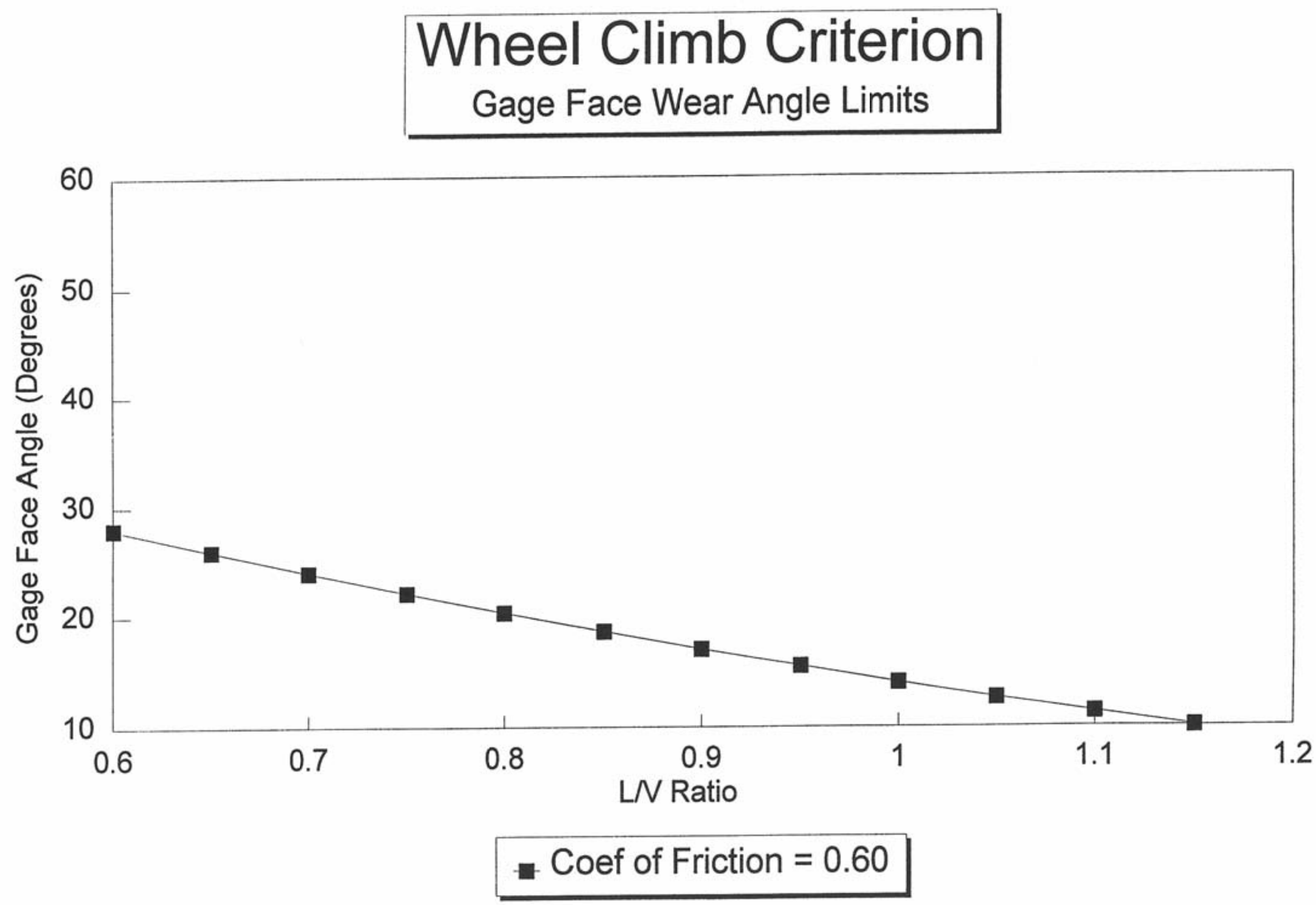

Wheel Climb Criterion
Gage Face Wear Angle Limits
Gage Face Angle (Degrees)
60
50
40
30
20
10
0.6
0.7
0.8
0.9
1
1.1
1.2
L/V Ratio
Coef of Friction = 0.60

Figure 8

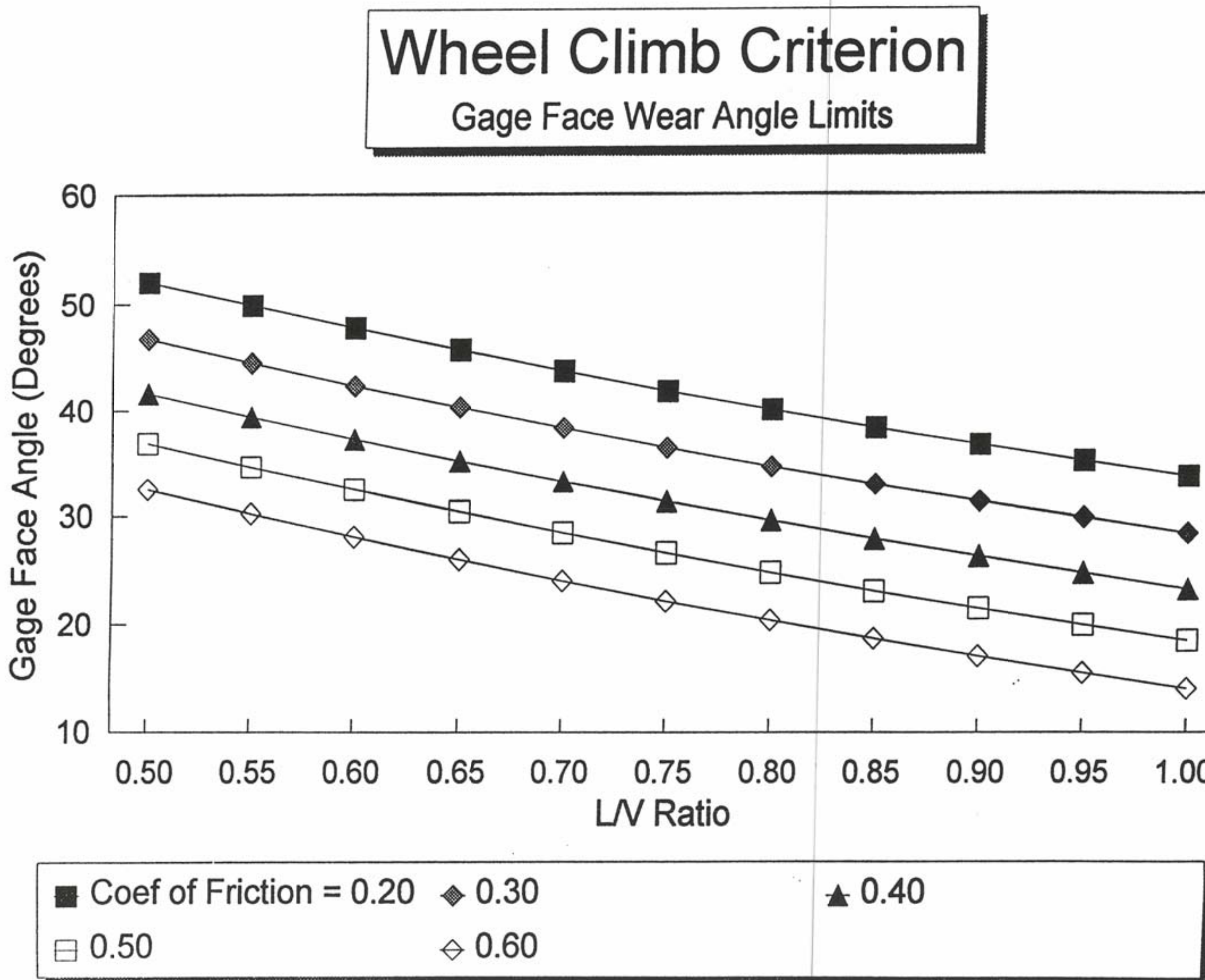

Wheel Climb Criterion
Gage Face Wear Angle Limits
Gage Face Angle (Degrees)
60
50
40
30
20
10
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
L/V Ratio
Coef of Friction = 0.20
0.30
0.40
0.50
0.60

Figure 9

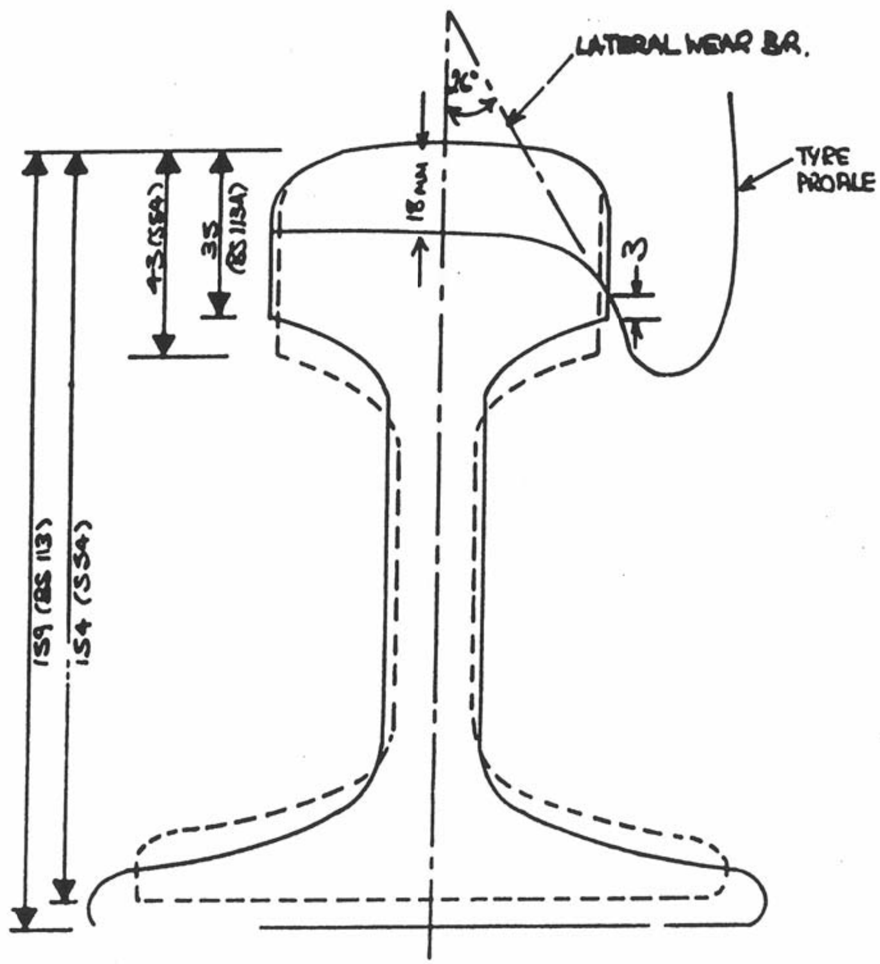


Figure 10: British Rail Standards