The Relation of Cylinder and Boiler Power in Locomotive Rating.

Paper No. 73.

E. M. Gass.

(See Vol. IX. No. 39, p. 276.)

COMMUNICATION.

Mr. Lawford H. Fry (Burnham, U.S.A.): As a former Member of Council who has watched with interest the growth of the Institution, I am glad to see a paper of this calibre laid before us. Manchester Centre is to be congratulated on starting their sessions on so high a plane. The Paper is a happy blend of "theory" and "practice." By "theory" I mean, not impractical *a priori* argument, but careful analysis of the fundamental principles of locomotive operation. Such theory checked, as in Mr. Gass's Paper, against results obtained in actual practice is a sure means, and the only one, of advancing our knowledge of the locomotive. In connection with this combination of theory and practice let me endorse most warmly what Mr. Gass, Mr. Lang and Mr. Rowland have said regarding the great benefits to be derived from a locomotive testing plant. The first plant of this kind was that at Purdue University under Professor Goss, which did pioneer work with small locomotives, the next was that of the Pennsylvania Railroad installed temporarily at St. Louis for the exhibition of 1904, and now permanently placed at Altoona. A third plant has been built by the University of Illinois, but has not done much work of importance. Anyone who has had an opportunity of seeing the work done by the Pennsylvania plant under Mr. C. D. Young, as Engineer of Tests, and Mr. J. T. Wallis, General Superintendent of Motive Power, will realise that the information obtained on the plant has enabled the Pennsylvania Railroad to base its recent work in locomotive design on scientifically accurate information instead of working as in earlier days by empiric methods only. To mention two specific cases in point, which bear on Mr. Gass's Paper. The question of the best tube length is referred to in the Paper and in the discussion as being still open. As a result of test plant experiments the Pennsylvania Railroad state quite definitely that when the flue length exceeds 100 times the interior diameter of the flue the increase in draught necessary to move the gases through the flues requires more steam than is gained by the very slight increase of evaporation due to the greater tube length. Again, the drop in boiler efficiency as the rate of combustion is increased has been shown to be due to a falling off in the efficiency of combustion and not to lack of heat absorbing capacity in the boiler. Mr. Rowland quotes the writer's analysis of the St. Louis tests as showing this. Further tests at Altoona have fully established this fact which was quite unsuspected until the accurate test plant experiments enabled the writer to work out exact heat balances for locomotive boilers. The test plant has shown beyond any doubt that for high boiler powers, grate area and combustion volume are more important than heating surface. This knowledge and that regarding tube length are of great practical importance. The large modern American locomotives require, in order to cover the wheel base, boilers of great length. In view of the knowledge referred to above the tendency is to keep the tubes of moderate length and take up the excess boiler length in providing a combustion chamber between firebox and flues. A very striking example of this is the articulated locomotive recently built by the Pennsylvania Railroad. The over-all length of the boiler is 53ft. 9½in.; Mr. Wallis has divided this to give a grate 14ft. long, a combustion chamber 13ft. long, with 19ft. tubes and 8ft. 6in. for the smokebox. This boiler has demonstrated its ability to evaporate 100,000 pounds of water an hour.

One or two members expressed disbelief in the practical results obtainable with the locomotive testing plant. Such disbelief can only come from ignorance of what the Pennsylvania plant has done and is doing. With a dynamometer car to determine car resistances on the various divisions, and the testing plant to determine the power of the locomotives at different speeds, the Pennsylvania Railroad has been able to establish tonnage ratings for each class of locomotive for all the divisions over which it operates, and to have these ratings lived up to in practice, allowance being made as necessary for weather conditions.

Returning to Mr. Gass's Paper, there are a number of points which deserve detailed discussion.

Starting Effort (page 279).—Mr. Gass raises a question as to the proper value to be taken for P, the mean effective pressure in the equation for maximum tractive effort.

$$T = PD^2S/W.$$

In this equation it is essential to define accurately the point at which the tractive effort is to be measured. Mr. Gass, though he does not say so explicitly, measured T at the piston rod so that P is the actual indicated mean effective pressure, and the internal resistance of the engine as well as the vehicular resistance of the engine and tender must be deducted from the tractive effort to find the draw bar pull. Under these conditions 82 per cent. of the boiler pressure is a low value to assume for P. The writer prefers to measure the maximum tractive effort at the rim of the driving wheels. The Baldwin Locomotive Works in following this practice have adopted the term "rated tractive effort" to express the maximum cylinder tractive effort at the rim of driving wheels calculated on the assumption that P is 85 per cent. of the boiler pressure. This is a reasonable assumption with American locomotives, as with a cut-off of 80 per cent., a deduction of 15 per cent. is sufficient to cover the loss of steam pressure from boiler to mean effective pressure, as well as the losses by friction between piston and rail. Mr. Weatherburn (page 347) gives an interesting curve bearing on this question. He shows that with an 0-8-0 superheater locomotive with a cut-off of 73 per cent., the maximum starting pull is that equivalent to a mean pressure on the pistons of 148lb. per sq. in., which is 82.5 per cent. of the boiler pressure of 180lb. per sq. in. The writer is very strongly in favour of adopting the term "rated tractive effort" as a standard designation for the cylinder tractive effort calculated from the formula with 85 per cent. of the boiler pressure as mean effective pressure. It may be that a given locomotive will not be designed to give a cut-off long enough to make the full rated tractive effort available at the rail, but in any case the rated tractive effort gives a quantity which measures the cylinder volume, boiler pressure, and driving wheel diameter; and an examination of the relation in which this quantity stands to the heating surface on the one hand, and to the adhesive weight on the other hand, gives most useful information regarding the proportions of the locomotive. The general use of 85 per cent. of the boiler pressure as the mean effective pressure to be used in calculating the cylinder tractive effort for purposes of comparison is desirable to ensure that all comparisons are made on the same basis. The American technical press, in publishing descriptions of new locomotives, always gives a number of ratios based on this 85 per cent. rated tractive effort, and the present writer has collected and commented on such ratios for over 400 European and American locomotives. In view of the amount of work already done on the

85 per cent. basis the use of a different value would lead to confusion and would give ratios which could not be compared directly with those already on record.

In the case of locomotives designed to avoid the use of cut-offs as great as 80 per cent. it will be necessary to note that the full rated tractive effort is not available, and to determine the maximum starting tractive effort. This will not however deprive the ratios based on the R.T.E. of their value in analysing the locomotive's proportions.

Cylinder Mean Effective Pressure.—Mr. Gass in Fig. 1 shows that the mean effective pressure available in the cylinder falls off as the speed is increased, and enumerates four factors (page 279) which contribute to this decrease. It would be well, however, to emphasise the fact that this variation in the mean effective pressure with the speed is more a question of boiler than of cylinder action. This can be very readily seen by Mr. Weatherburn's curve (Fig. 12 on page 348). This shows that as the speed increases from 3 miles per hour to 24 miles per hour with a constant cut-off of 73 per cent., the draw bar pull drops from 12.4 tons to 7.6 tons, but the draw bar horse-power increases from 200 to 1,100 h.p. Mr. Weatherburn does not give the boiler power of the engine, but as Mr. Gass shows in Table A (page 294) a maximum boiler horse-power of about 830 for the L. and Y. 0-8-0 engine, it seems probable that making due allowance for the advantage of superheat the N.E.R. engine will develop not more than 950 horse-power at the draw bar. It will be seen from Fig. 12 that the cylinders require this horse-power at about 17.5 miles per hour. It is therefore obvious that if an attempt is made to run the locomotive with 73 per cent. cut-off at more than 17.5 miles per hour the boiler will be run out of steam. In order to maintain a higher speed, the cut-off must be shortened, which reduces the tractive effort. The steam required by this cut-off will balance against the steam producing capacity of the boiler at some speed higher than 17.5 miles per hour, and then for a further increase in speed a further reduction in cut-off, and hence in tractive effort, will be necessary. It is evident from this that if two locomotives have the same cylinder and driving wheel dimensions and the same boiler pressure, that is the same rated tractive effort, but have different boiler capacities, it will follow that the speed up to which a given cut-off, and the tractive effort corresponding to this cut-off can be maintained, will be greater for the engine with the greater boiler capacity. Therefore the mean effective pressure which can be maintained at a given speed depends on the relation between rated tractive effort (cylinder capacity) and boiler capacity. In general comparisons it is usual to assume that in properly designed locomotives the steam producing capacity is proportional to the heating surface.

On this basis the position of the curve giving the relation between mean effective pressure and speed will depend on the ratio of boiler heating surface to rated tractive effort. This is illustrated by the curves in Fig. 14, taken from locomotive data published by the Baldwin Locomotive Works. In this Fig. the ordinates to the curves give the tractive force available at the rim of the drivers in per cent. of the rated tractive effort, and different curves are given for different values of the ratio, rated tractive effort divided by heating surface.

Engine and Train Resistance.—It is gratifying to find that the writer's formula for car resistance gives satisfactory results, but the figures given for engine resistance appear to require further study. It is hard to believe that the curves given in Fig. 2 represent accurately the internal or machinery resistance. There is no good reason for believing that if the two engines were in proper condition the 0-8-0 engine would show a resistance of 20lb. per ton while the 0-6-0 engine gave only 8lb. per ton at the same speed. The difficulty evidently lies in the method used for the determination of these resistances. The total tractive force was calculated from indicator cards and the drawbar pull measured by a dynamometer car and the difference, 5.0 per cent. of the total tractive force for the 0-8-0 engine and 3.5 per cent. for the 0-6-0 engine, taken as engine resistance. The disadvantage of this method is that it is not easy to measure the total tractive force or the draw bar pull with an accuracy of 1 in 100, and an error of one per cent. in either of these measurements makes an error of from 20 to 30 per cent. in the measurement of the engine resistance. The writer has tried various formulæ to express the variation in the internal resistance with the number of coupled axles, but has come to the conclusion that in view of the fact that measurements of the engine resistance are not usually exact and that, as a moderate variation in the engine resistance is of little effect on the weight of train that can be hauled, it is better to assume that the internal or machinery resistance of the engine is a constant percentage, say eight per cent., of the tractive force developed. If this is done, however, the vehicular resistance of the locomotive and tender cannot be taken on the same basis as the train, but must be made to

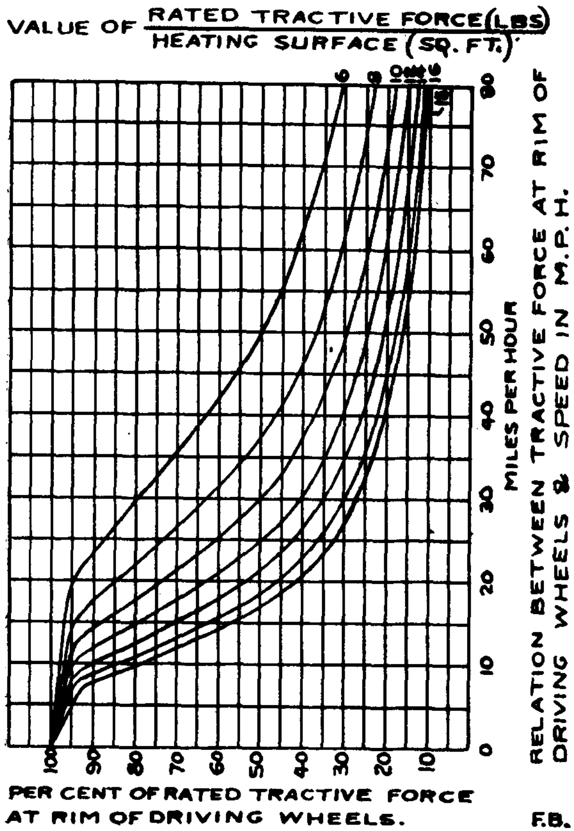

FIG. 13.

Illustrating Mr. L. H. Fry's Remarks.

rise more rapidly with the speed to take into account the head resistance. The Baldwin Locomotive Works recommend that for the resistance R in pounds per ton of locomotive and tender the formula $R=5.0+0.0040\ V^2$ be used where V is the speed in miles per hour. Calculated on the above basis the 0-8-0 locomotive at 15 miles per hour would have about 3 per cent. more hauling capacity than given by Mr. Gass on page 283. This is not a serious difference, but the principles involved deserve attention.

The question of a streamline prow for the locomotive was referred to in the discussion. Such a prow would reduce the head resistance in a calm or with a wind dead ahead. It must be remembered, though, that the greatest increase in resistance comes from a quartering or a side wind blowing the train against one rail and thus increasing the flange resistance, and to such winds a prow would offer increased surface.

Boiler Power.—Mr. Gass's notes on boiler power deserve very careful attention, particularly the statement that the boiler cannot be too large. Forty or more years ago Mr. N. N. Forney said that the best rule for proportioning a boiler was to make it as large as possible, and this remains true to-day. In this connection, and noting Mr. Spencer's discussion on page 352, the writer mentions that he has found it useful in studying locomotive proportions to consider three ratios or factors :—

A = Weight on drivers/rated tractive effort = Factor of adhesion.
B = Rated tractive effort/heating surface = Boiler factor.
C = Heating surface/grate area = Combustion factor.

A tabulation of these and other ratios for over 400 European and American locomotives will be found in "The Engineer" for October 13th, 1911. The boiler factor B will vary with the type of locomotive, being normally lower for high speed than for low speed engines. Average values of this factor in American practice are :—

Atlantic type (4-4-2)	8
Pacific type (4-6-2)	9
Four-coupled type (4-4-0) ...	10
Mikado type (2-8-2)	10
Ten-wheeled type (4-6-0) ..	11
Consolidation (2-8-0) ...	14

Steam per Indicated Horse-Power Hour.—The curve in Fig. 10, described by Mr. Gass on page 292, is most interesting. It shows a consumption of 30 pounds of steam per horse-power hour at slow speeds, a minimum of 25 pounds per horse-power hour at a speed of 600 feet per minute, and a return to the maximum consumption of 30lb. per horse-power hour at the maximum speeds. This is quite in accordance with the results obtained on the locomotive testing plants, but the writer agrees with Mr. McArd, that for such comparisons the number of revolutions per minute is a better basis of comparison than the piston speed. The greatest loss of efficiency of the steam is in its entrance to and exit from the cylinder, and not during the time it is following the piston. Therefore the cylinder efficiency is more closely connected with the number of revolutions than with the piston speed. It should be noted that the cylinder efficiency increases as the speed increases up to a certain critical speed, which from Fig. 10 is 600 piston-feet per minute or 138 r.p.m. with 26in. stroke. This increase in efficiency is due to the shortening of the cut-off. Beyond the critical speed, however, an increase in speed causes a decrease in the cylinder efficiency. That is to say there is a certain critical cut-off at which the cylinders use the least steam per horse-power hour, and a change from this condition either by lengthening or shortening the cut-off reduces the efficiency. This knowledge is of the greatest importance in designing a locomotive to secure the greatest possible efficiency. The cylinders and driving wheels should be proportioned so that under the most frequently occurring conditions of speed and power the engine can work with its most economical cut-off. The curve in Fig. 10 is comparatively flat near the maximum efficiency, so that a fairly wide range of speeds can be obtained without an undue variation in the cylinder efficiency.

In the discussion of the paper Mr. Holcroft and Mr. Mercer argue against the usefulness of locomotive testing plants. The objections raised would disappear on visiting the Pennsylvania plant at Altoona. Among the objections are "absence of vibration, irregular turning at low speeds, low coefficient of frictions on rollers preventing development of full draw bar pull." A single visit to the Altoona plant of the Pennsylvania Railroad would dispel such illusions. Smooth riding may or may not affect the steaming power of the boiler, probably not, but the locomotives ride so much more roughly on the plant, the cushioning effect of the permanent way being absent, that the drivers consider the discomfort deserves a bonus for running on the plant. To develop full drawbar pull requires the addition of a special counterbalance, but with this the Pennsylvania 2-8-2 engines have run at 91 per cent. cut-off and 40 r.p.m. developing a drawbar pull of over 59,472 pounds, which is 25 per cent. of the weight on drivers. Road tests have their uses, but there are very few roads which can arrange for a run of an hour under constant conditions without any variation of grade, speed, or cut-off. Such conditions are necessary to determine the steam consumption at a given cut-off, and can be easily carried out on a testing plant. Mr. Rowland's method of estimating boiler efficiencies, page 321 *et seq.*, is most interesting and deserves a whole paper to itself, so that the equations he offers could be shown in relation to the tests from which they are derived. The writer hopes that Mr. Rowland will contribute further information on this subject, in the meantime one or two points deserve attention. Mr. Rowland distinguishes between heat absorbed by firebox by convection and that absorbed by radiation, and calculates the latter amount of heat on the assumption that the radiating surface is the grate area plus one-half the firebox surface. The writer does not believe that any experimental data is available to enable such a division between converted and radiated heat in the firebox to be made. Further, the writer's understanding of the phenomenon of radiation in a flame filled firebox is, that each particle of flame not in contact with the surface of the box, receives by radiation as much heat as it gives out, and consequently the actual radiating surface is that of the flame in contact with the surface, that is, is the same as the firebox heating surface. The writer's practice in such calculations is to assume that the convected heat in the firebox has a negligible effect and to calculate the radiation by Stephan's formula as used by Mr. Rowland, but applied to the total firebox heating surface. Mr. Rowland's formula for the efficiency of the tubes is ingenious, but it can only be applicable in a comparatively narrow range of conditions, as it does not take into account the rate of flow of gas through the flues.

In conclusion the writer would like to express again his admiration for the Paper and the discussion it brought out. If the Institution can maintain its meetings at this standard Mr. Kidd's remark that more good locomotive literature is produced in America than in Great Britain will very soon be no longer true.