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"FAVOURABLE POINTS IN FOUR CYLINDER DESIGN LOCOMOTIVES."

BY

Mr. W. H. PEARCE (Member).

In the present paper the Author proposes to consider points in the design of the Great Western four cylinder engine, which has proved so efficient under all conditions of service, rather than attempt a general survey of the evolution of four cylinder engines.

The essential features that make for maximum efficiency combined with a minimum of disturbing forces are so involved that they do not lend themselves to a mathematical treatment and, therefore, the Author proposes to deal with his subject from a practical standpoint only. It will be admitted that the results of practical tests are invaluable as they have a direct influence on future design and help to clear up points which are not easily settled by theoretical methods. As an example, theory indicated that the valve lead in mid-gear should be about one-third of the steam lap whereas, by practical tests, it has been shown that the lead may be reduced by fifty per cent. and the steam lap increased by fifty per cent. with improved efficiency. These tests were carried out on two cylinder engines prior to the introduction of the four cylinder design and, settling many disputed points in regard to the steam distribution, made the path clear for the cylinder and valve proportions of the latter type.

The trend of present day development is to seek variation in the design of the "power unit" rather than in the "boiler unit" the design of which is more settled and capable of easy adaptability to various classes of engines. Such development requires a thorough and detailed study of such questions as correct steam distribution, reciprocating motions, moments of tractive effort exerted at the cranks, forces acting in the coupling rods, the thrust on the axlebox guides and correct balancing.

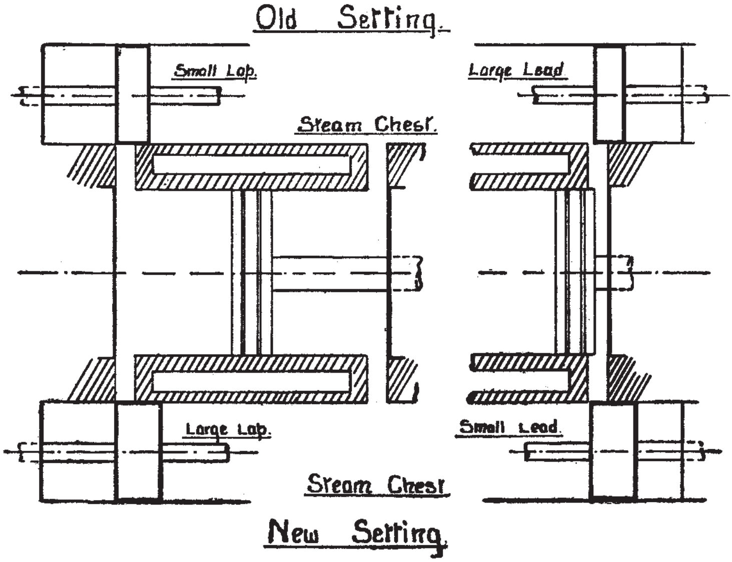
Old Setting.
Small Lap.
Large Lead
Steam Chest.
Large Lap.
Small Lead.
Steam Chest
New Setting.

Fig. 1.

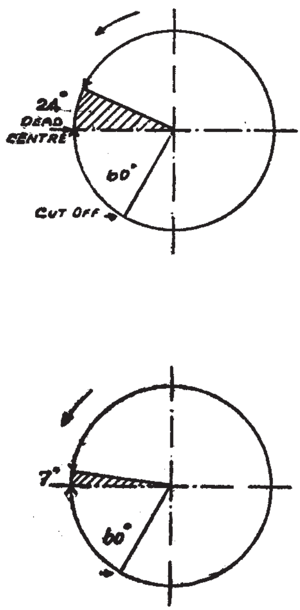
24°
DEAD CENTRE
60°
CUT OFF
7°
60°

Fig. 2.

Previous to the adoption of efficient valve proportions the effect of unbalanced reciprocating weight was counteracted by the steam distribution, thus necessitating excessive compression and lead with the result that negative work was being done by the steam. With the modified valve proportions a much greater percentage of the total energy in the steam is converted to useful work.

As locomotive power increased there was a marked disturbance in those revolving masses which contained weight for the counter-balancing of reciprocating masses. To reduce such disturbing forces to a minimum a more complete balance was required and it was therefore necessary to adopt a practically complete balance of reciprocating weight by reciprocating weight. This meant that similar sets of reciprocating masses had to be given opposing motions over the same equal and opposite angles of revolution. If the motions are not so opposed the balance is incomplete and it is necessary to balance by means of rotating masses. The smaller the rotating masses so used the smaller the hammer blow on the rail, the smaller the variation in rail load and the better the acceleration. With complete balance by reciprocating masses the whole static load on the wheel is available for adhesion.

Slipping may be due either to a variation of the adhesive force between the rail and the wheel or to a variation in the effort exerted by the engine. A variation in the former is dependent on the rail resistance and the axle load. The resistance of the rail depends to a certain extent on climatic conditions, but when complete balance is obtained by reciprocating masses the axle load remains constant so that the chance of slipping is very much reduced.

The variations in the effort exerted by the engine are developed at each revolution, the difference being greatest at starting . With an increase of speed the difference is considerably reduced by virtue of the fact that the steam is working expansively when the cranks are in the position of maximum turning effort. With four cylinder engines there is a maximum power impulse at each quarter revolution, but the impulse energy is imparted to the rotating masses with such an effective force that its momentum assists the minimum impulse. Due to the minimum of unbalanced forces the negative work is practically nil. In fig. 3 the full line shows the torque curve for four cylinders as compared with that for three cylinders shown by the dotted line.

The fact that there is a pronounced peak in the turning effort at each quarter revolution needs careful analysis. There is no dispute as to the advantage of such a peak at starting. The force required to start a train from rest is beyond the range of practical calculation, but a momentary application of this force suffices to put the train in motion and a much smaller force only is required thereafter. The Great Western four cylinder design gives the momentary maximum turning moment required for starting. This advantage is noticeable in all periods of suppressed cut-off, and permits this type of engine to be run in twelve per cent. cut-off at high speed with a draw bar pull unequalled by other crank arrangements at this degree of expansion. The advantage of engines with a large turning effort peak at each quarter revolution is more apparent when bank

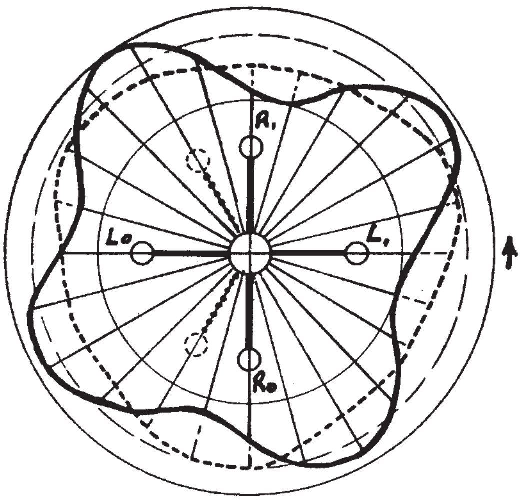

Fig. 3.

working is considered. It is not unusual to find sections of line where the maximum train load is limited by the gradient and to increase this load it is necessary to provide an additional engine to assist up the bank. It would be an advantage to use two engines of the four cylinder type for this class of work, since the chief difficulty lies in starting on an up gradient, and this class of engine would be able to exert the large momentary effort required. Especially is this the case when the adhesion is so arranged that there is an ample margin to provide against slipping, even when the coefficient of friction is reduced by climatic conditions. In most cases sufficient adhesive weight is available, owing to the fact that a large capacity boiler is essential for maintaining the reserve of energy demanded in bank working. The fact of an engine slipping is direct evidence that the cylinders are capable of exerting more force than can be harnessed by the particular distribution of weight and arrangement of wheels to which they are connected. It would thus appear that the effective power of the engine is dependent on the peak effort rather than on the effort given by the mean height of the turning effort diagram and, though perhaps a debatable point, the results obtained would certainly appear to justify the design in which these features are embodied.

It might be considered that the erratic demand made upon the boiler at each quarter revolution would be a disadvantage, but this is counteracted by providing a large steam chest capacity, and it is found that the variation in the steam chest pressure line is then very slight.

The above consideration raises the question of intermittent exhausts. The function of the exhaust tip must be considered from the two practical points of view of back pressure and smokebox vacuum. In order to obtain a large indicator diagram it is necessary to release the exhaust steam at as low a pressure as possible, and therefore the blast pipe orifice should be as large as possible, consistent with good steaming. It was found, in the manner about to be described, that decreasing the blast pipe pressure variations resulted in poor steaming. On certain engines the volume of the exhaust passages was considerably increased and a chamber, or reservoir, was formed for the exhaust from the cylinder before it reached the blast pipe orifice. In service the arrangement did not give results equal to those obtained with pronounced intermittent exhausts. Since it is the peaks of smokebox vacuum which are the most effective, the four cylinder has a natural advantage over the three cylinder type, inasmuch as it has only four beats per revolution as against the six beats of the latter. It has also been found that the blower, which maintains a constant vacuum, does not produce such good steaming as intermittent exhausts creating the same average vacuum with a maximum at each quarter revolution. When the blower is used continuously it is necessary to make much more frequent use of the fire pricker, in other words, the momentary disturbing effect of the gases have to be reproduced mechanically when the intermittent effect is absent. When working slowly in full fore gear the exceedingly heavy beats, which would disrupt the fire, are reduced automatically by the "jumper" blast pipe top. Fig. 4 shows the standard "jumper top."

As previously stated, in order to minimise the proportion of the reciprocating masses to be balanced by rotating masses, it is necessary to arrange the cranks so that as one moving part acquires momentum in one direction, another similar part acquires an equal momentum in the opposite direction. This means that the frames are relieved of considerable stresses which would otherwise fall upon them and is of great benefit to the axlebox guides.

The cushioning, by compression of the steam, of the momentum acquired by the reciprocating parts is more perfect when the four cylinders are driving one pair of wheels. With two cranks on the leading wheels and two on the next pair of coupled wheels (G.W. design), the balance of resistance has to be taken by the frame or by the coupling rods when slipping. This resistance should be very small and would be nil when the inside and outside connecting rods are the same length.

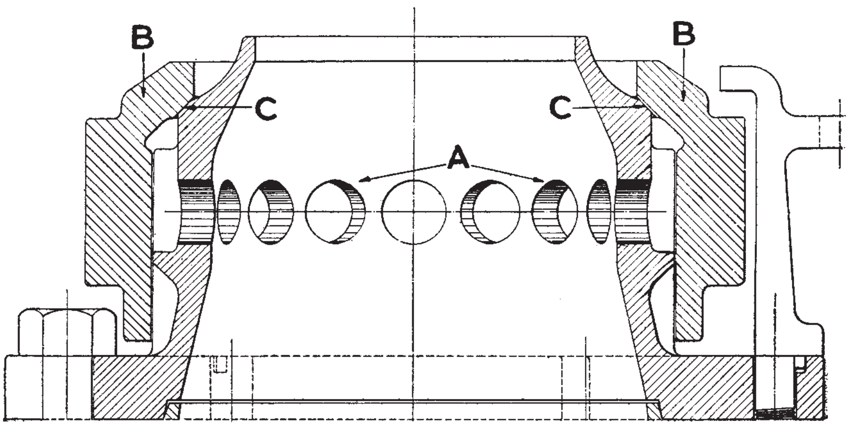

Fig. 4.

Having pointed out where initial disturbing forces are likely to occur, and shown the conditions under which these are reduced to a minimum, the next consideration is the development of a more complete balance by the use of balance weights. If similar reciprocating masses are made to move through equal angles of revolution in opposite directions, it might, at first sight, appear that a complete balance had been obtained. Though approximately true when only one driving axle is used, perfect balance is only attained when the opposing masses act in the same plane but, since these masses act in different planes, there is a slight disturbing effect which can be easily balanced by rotating masses with only a small resistance to the turning effort. In the four cylinder engine there is no tendency to lateral stress, since one half of the force is applied to each side of the engine with one quarter on each side of the main frames.

The peak in the turning effort, previously referred to, can be made more marked in modern engines by suitable alteration of the valve proportions alone, provided that an efficient valve gear is employed. A few valve gears have been analysed and by simple graphical methods it is possible to lay out, or develop, the centre lines of a motion that will give the correct movement for each link in the mechanism.

A choice of valve gear needs consideration in respect of a previously selected arrangement of cylinders, and evidence of results obtained from Walschaerts gear led to the conclusion that it was worth re-designing to suit the conditions of a four cylinder arrangement. The advantage of the four cylinder design over others was anticipated before the results of practical tests were added as conclusive proof, but the superiority thus experienced was due in no small degree to the provision of a Walschaerts valve gear. An efficient valve gear is one in which the correct distribution is maintained, in accordance with the approved setting, from one general repair to the next. Obviously this necessitates reducing the number of working surfaces to a minimum, and careful design enabled a gear to be provided having a total of only twenty-eight pin joints. The same gear as modified for the latest three cylinder engines would also require twenty-eight pin joints, whilst on a four cylinder engine with separate gears forty joints would be required.

From a standpoint of steam distribution a measure of the efficiency of the engine is the minimum possible cut-off with a given load at high speeds. For a load of three hundred and fifty tons at a speed of sixty miles per hour this was found to be sixteen per cent. for Great Western four cylinder engines. This position of cut-off practically coincides with the point of maximum expansion, as can be shown by drawing valve diagrams for each point of cut-off and plotting the expansion periods on a cut-off base line. If this cut-off be either increased or decreased then the efficiency and working economy will be lowered. A heavier load could be worked in a later cut-off but the engine would be forced unduly and the boiler would be working at its maximum capacity; it would, therefore, be more economical to increase the tractive effort of the engine to such a figure that the train could again be worked in sixteen per cent. cut-off if heavier loads were to be the rule. In such problems as these the question of boiler capacity calls for detailed study but such a subject would provide sufficient material for another paper.

It is the usual practice to aim at equalised cut-offs in all four cylinders, but it can be shown that if this were the final valve setting there would be an interval of time between the two exhausts of the two cylinders on the same side of the engine, due to the angularity of the connecting rods. It is therefore necessary to make a correction so that the exhaust from each pair of cylinders will take place at precisely the same instant. If this were not so there would be eight exhaust beats per revolution, with unequal intervals of time between them, that is, four pairs of exhaust beats.

The cylinder ratios also, have a pronounced bearing on the efficiency of the engine and, therefore, the ratios which had proved so satisfactory in the two cylinder engines were adopted for the four cylinder type.

Great stress has been laid on the value of correct valve proportions because in this way only, can full use be made of the possibilities of high steam pressures and consequent high steam velocities and thus obtain a fuller indicator card, meaning greater indicated horse power. This point is clearly shown in fig. 5.

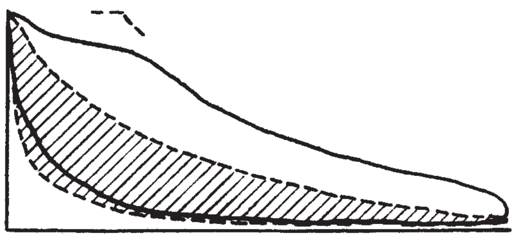

Fig. 5.

The practical application of these notes should be fairly visualised by most listeners to this paper, since the materialised product has been before them for a number of years. With the exception of the original engine, practically no alteration has been needed since the class first appeared.

The original Great Western four cylinder engine differed in the arrangement of the valve gear, which was so designed that all valve motion was taken from the crossheads only. If the valve motion is derived from any further source, such as by additional eccentrics, then there is need of slight correction for angularities but, on the other hand, the right and left-hand engines may be made independent of each other thus facilitating working home in case of a failure on one side. With the original design it is necessary to rely on both inside connecting rods being kept in motion in order to work the engine home. This design is still in service and no occasion to report against its efficient working has yet been noted.

With the eccentric arrangement as used on all other Great Western four cylinder engines at the present time, a disablement of the two outside cylinders or of the two cylinders on one side of the engine still leaves fifty per cent. of the total power available for working home. With three cylinder engines using the combination lever valve arrangement the disablement of one cylinder with the attached primary valve gear leaves only thirty-three per cent. of the power available for working home. Taking the minimum of disablement, one outside cylinder on four cylinder engines leaves seventy-five per cent., whilst one outside cylinder on three cylinder engines leaves only sixty-six per cent. available power.

In conclusion the Author wishes to thank the Chairman for the helpful suggestions which he made in the writing of the paper.

DISCUSSION.

In opening the discussion the Chairman (Mr. O. E. F. Deverell) said they were very much indebted to the Author for the information which he had placed before them. Mr. Pearce was well qualified to read such a paper by reason of his varied experience in the design and subsequent running of the locomotive.

As Great Western men they were proud of their four cylinder engines, and the information which the Author had given them confirmed their pride. Other locomotive engineers would tell them that the three cylinder type was as good as, or even better than, the four cylinder locomotive by reason of a more even turning moment and a more even blast. It was claimed that the six exhaust beats per revolution of the three cylinder type did not lift the fire so much at starting as did the four exhaust beats of the G.W. four cylinder design. This difficulty, if it were so, was overcome by the use of the jumper top on the blast pipe, which came into operation when the engine was working heavily.

Mr. C. T. Cuss said that at a meeting of the Society some twenty years ago, Mr. Churchward, in the chair, said that engineers should apply themselves to obtaining a more uniform torque on the crank shaft. The Author had shown them in his paper how this was to be done. He gathered that there were four main reasons for the success of the four cylinder locomotive:

(1) There were eight impulses per revolution instead of four as in the two cylinder locomotive, thus making the locomotive more like the internal combustion engine.

(2) The more uniform torque.

(3) The more efficient steam passages.

(4) The ability of the boiler, due to the better circulation and the use of superheated steam, to meet the large demands made upon it.

He would like to ask the Author whether the jumper top was in operation throughout the whole of the journey.

Mr. H. G. Kerry was interested to hear that the effect of the exhaust on the fire was more beneficial than the use of the blower and wondered if any type of intermittent blower had been tried.

Mr. J. E. Bagguley thought that a more even draught through the fire was to be preferred and asked what effect an intermittent blast would have on the coal consumption.

Mr. C. K. Dumas remarked that one point in favour of the four cylinder engine was the splitting up of the work between two axles and the consequent reduction of the working stresses. The better balance of the four cylinder type constituted a great advantage and he thought that due allowance should be made for this by the Engineering Department, who had not up to the present allowed any more load per axle than was the case with the two cylinder locomotive. When plotting torque curves from indicator cards he had found some showing a remarkably even torque. The drawbar pull was, however, not more even where these cards were taken than elsewhere, which seemed to imply that correct balancing was more important than an even torque.

The Author, in reply, agreed that the working of a four cylinder locomotive more nearly approached that of the internal combustion engine. In the latter, the work was done by peak loads, and he would suggest that the peak effect on four cylinder engines contributed to their high efficiency. The introduction of piston valves had also played a large part in the success of the four cylinder locomotive. It was essential that the valve settings should be correctly determined as, at a speed of 60 m.p.h., the ports were opened and closed in one-twentieth of a second. Although giving less trouble than formerly, the boiler power marked the limit of engine performance and it was therefore necessary to strive for maximum efficiency in the cylinders. The jumper top only came into operation at cut-offs later than thirty per cent., when the large volume of steam exhausted had a tendency to disrupt the fire. At ordinary running cut-offs the normal blast pipe orifice was sufficient.

In reply to Mr. Kerry, he was not aware of any instance of an intermittent blower having been tried, but thought that it would have to be a very ingenious arrangement to function correctly at high speeds.

In reply to Mr. Bagguley, the Author thought the more even draught of the three cylinder type would result in a slight increase in coal consumption when compared with the four cylinder engine.

In reply to Mr. Dumas, it was the standard practice on the G.W. four cylinder engines to divide the power between two axles. In two cylinder locomotives there was a hammer blow of from six to eight tons compared with a much smaller figure for the four cylinder type, so that he agreed with the speaker that the permissible axle load could be raised for this type of engine.

Mr. K. J. Cook said that he could not agree with the statement sometimes put forward, that bank working placed the heaviest strain on the boiler. Although this class of work required more steam per unit distance there was more blast to produce that steam. When running at high speed on a moderately level road the steam required per unit time was much higher and the blast must be sufficiently heavy to maintain the higher rate of coal consumption. When the cylinders of the three cylinder type were all in line it facilitated the making of a solid joint between the steam pipes, but the wisdom of casting the three cylinders in one block was to be questioned since if one cylinder were damaged the whole set would have to be scrapped and also, due to a certain amount of racking motion, the cost of maintenance in the running sheds was increased. Referring to the question of increased axle loads the advocates of the three cylinder engine claimed that it was more even in running than the four cylinder type.

The Author, in reply to Mr. Cook, said that the correct disturbance of the fire undoubtedly had a great effect upon the coal consumption. He also agreed that difficulties had been experienced with the steam pipe joints due to the racking motions set up. With the modern form of valve gear casting this effect had been greatly reduced and with the introduction of outside steam pipes had been entirely eliminated.

Mr. J. G. Jones said that in the majority of three cylinder engines the inside valve gear was driven directly from the outside gears with the result that should either of the outside gears be damaged the whole engine was disabled, whereas with the four cylinder type the locomotive could work home on one side. In the Holcroft system of three cylinder locomotives the rocking lever connecting the inside and outside valve gears had a ratio of 4 to 1 with the result that the effect of any wear at the pin joints was considerably multiplied and bad steam distribution would ensue. He could not agree that the secret of the high efficiency of the four cylinder locomotive lay in the peak effect of an uneven torque curve. An uneven torque implied larger cylinder dimensions for the same output, an increase in the diameter of the crank shaft in order to reduce the stresses caused by the increased maximum torque, greater risk of slipping and the setting up of heavier strains in the frame of the engine. He could not see that any comparison could be drawn between the performance of an internal combustion engine and that of a steam locomotive. In the former the energy of one explosion was spread over four strokes whereas with the steam engine each stroke was a power stroke.

The Author, in reply to Mr. Jones, said that uniform torque could only be obtained at the expense of a reduced torque at starting. The peak effect increased the available torque at starting by something like 12% and were this not available it would, in extreme instances, necessitate the use of a banking engine.

Mr. R. F. Wallington said that, granted perfect balance was obtained on four cylinder engines with regard to the primary forces, he would like to know whether any attempt was made to balance the primary couples and also what effect had secondary forces and couples at speeds in the neighbourhood of eighty miles per hour. Could the Author give them any information with regard to the operation of Jumper Tops, as he had noticed several coming in for repair which were so badly carbonised that it was impossible for them to work.

The Author, in reply, said that it was possible to balance primary couples far more accurately in the case of the four cylinder engine than was possible with either the three or two cylinder types since the centres of the outside and inside cylinders were practically at the same distance from the frames. This, of course, resulted in a much reduced flange wear for the four cylinder locomotive. At high speeds the most serious consideration was that of hammer blow set up by the balance weights. Jumper Tops had given every satisfaction in service, and although fitted to nearly all engines only a very small percentage were found that did not lift. Brushes were supplied with which to keep the tops clean and any deposit could be softened with paraffin.

In closing the discussion, the Chairman said that they were all very grateful to the Author for the trouble which he had taken in the preparation of his paper.