[No 92.]

G.W.R. Mechanics' Institution.

SWINDON ENGINEERING SOCIETY.

TRANSACTIONS, 1908-9

SECOND INTERMEDIATE MEETING.– March 16th, 1909.
Chairman – Mr. C. T. Cuss.

"ARRANGEMENT OF LOCOMOTIVE CYLINDERS,"

BY
H. HOLCROFT (Member).

In order that a locomotive may be started from rest under full load, two cranks are required, each set at right angles to the other, so that when the piston in one cylinder is at the end of its stroke, giving no turning moment to the axle, the other is about mid-stroke, giving its maximum turning moment.

If only one cylinder were used the probability is that, though the engine would start, say, three out of four times, it would fail to do so the fourth ; this alone is sufficient to entirely preclude its use, otherwise it presents the advantage of lightness, cheapness, and the minimum cylinder surface area, in comparison to piston area, but unfortunately such an engine is not practicable.

With two-cylinder engines there are two arrangements in general use : the cylinders may be situated between the frames or on the outside of each frame, and in both cases are placed horizontally, or nearly so, and, with few exceptions, are located at the leading end of the engine.

Inside-cylinder engines were almost universal in this country until recent years, but in America the reverse is the case, as there seems to be a prejudice against the crank axle there. The increasing demand for locomotive power has necessitated the building of powerful engines, such as the Atlantic type, and 6-wheel coupled engines with the cylinders placed outside the frames. With such engines there

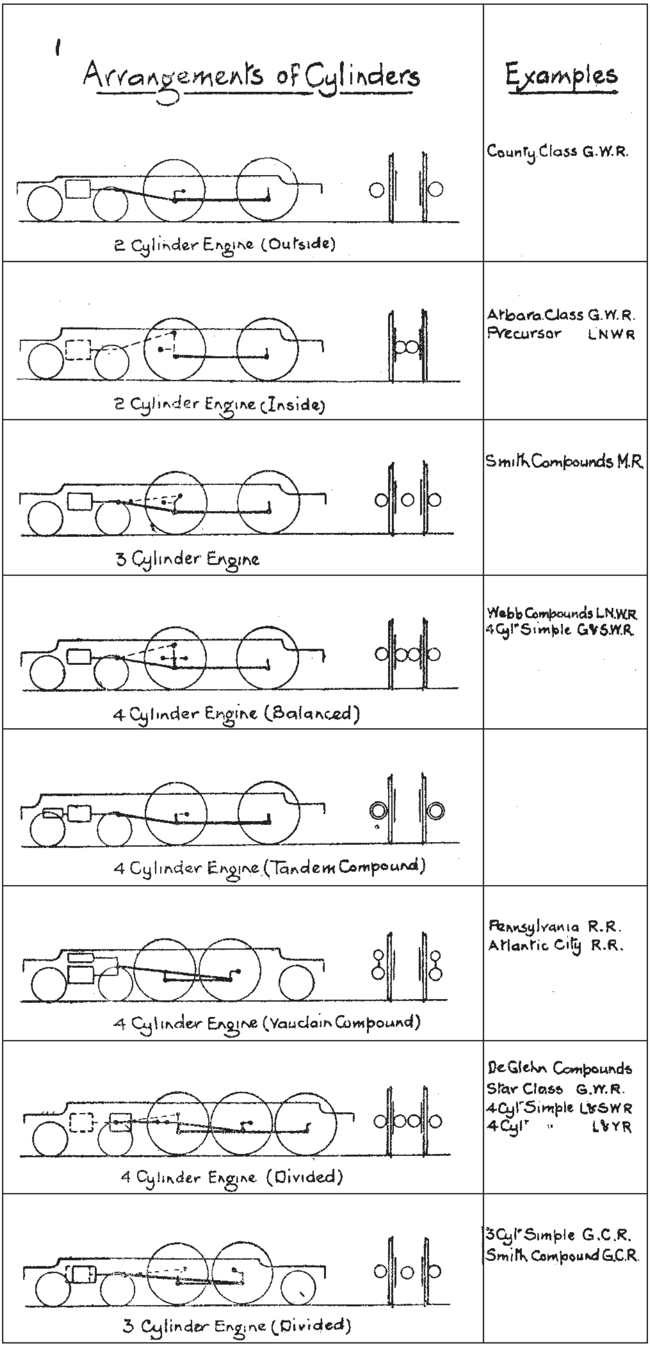

1
Arrangements of Cylinders
Examples
County Class G.W.R.
2 Cylinder Engine (Outside)
Atbara Class G.W.R.
Precursor LNWR
2 Cylinder Engine (Inside)
Smith Compounds M.R.
3 Cylinder Engine
Webb Compounds L.N.W.R.
4 Cyl[r] Simple G&S.W.R.
4 Cylinder Engine (Balanced)
4 Cylinder Engine (Tandem Compound)
Pennsylvania R.R.
Atlantic City R.R.
4 Cylinder Engine (Vauclain Compound)
De Glehn Compounds
Star Class G.W.R.
4 Cyl[r] Simple L&SWR
4 Cyl[r] " L&YR
4 Cylinder Engine (Divided)
3 Cyl[r] Simple G.C.R.
Smith Compound G.C.R.
3 Cylinder Engine (Divided)

FIG. 1.

are drawbacks to the application of inside cylinders, which drive on the leading pair of coupled wheels instead of the second pair, as with outside cylinders, consequently the connecting rods are very short, unless the wheel base is lengthened to an objectionable amount. The large diameter of cylinders and high boiler pressure throw heavy stresses on the crank axle, giving it a very short life ; the crank axle also limits the stroke, since 13 inches seems to be as far as it is desirable to carry the throw of the crank. Another point is that in 4-4-0 type of engines the firebox can be longer for a given wheel base with outside cylinders, as it can be brought closer to a straight axle. These are some of the chief reasons for the increasing use of outside cylinders in this country. However, in spite of the disadvantages, inside cylinders are used in the 4-4-2 type on the L. & Y. R. and in the 4-6-0 type on the L. & N. W. and Caledonian Railways.

In comparing inside and outside cylinders, there is with inside cylinders not so much loss of heat, as the smokebox transmits heat to them, and replaces some of that lost by the sides and ends, consequently there is less condensation.

The turning moment is the same in each case, but the position of the cylinders affects the balancing of the engine, and consequently the variation in rail pressure or hammer blow.

In considering the balancing of the engines, the balance weight is split up into its components and analysed, and the proportion balancing purely revolving masses is not taken into consideration, as it does not enter into the question, thus leaving only the proportion balancing the reciprocating masses. This weight in each wheel is the resultant of two components into which it is again split, and in, say, the left hand there is a large weight opposite to the left hand crank, and a small one at right angles to it, balancing forces on the right hand side of the engine, and in the right hand wheel *vice versa*. Owing to the weight not working in the same plane as the cylinder an unbalanced couple is set up, and the small weight is introduced into the opposite wheel to complete the balance (Fig. 2). It will be seen that this small weight is opposite its crank with inside cylinders, and on the same side with outside.

With inside cylinders there is less difference in the sizes of the two component weights, consequently there is less variation in rail pressure than with outside cylinders. This variation does not occur in each wheel at the same time, but about a quarter of a revolution apart ; it is therefore to be expected that an inside engine will run more steadily, as the disturbing forces are less. At the same time several advantages arise from the use of outside cylinders : there is more room for such things as vacuum brake cylinders and reservoirs, inspection is easier, longer bearings can be used, and no crank axle is necessary ; better staying of the frames also can be arranged. Again, on the other hand, with inside cylinders a small throw may be used for the coupling rods, as with outside the throw depends on the stroke of the cylinders, unless the pin is turned eccentric to reduce the coupling rod throw ; but this can only be done to a limited extent.

Two cylinder compounds have been used in this country, but the size of the low pressure cylinder was restricted, both between the frames and outside : they are in use in Ireland, where the wider gauge gives more room between frames, and in America, where the load gauge permits of their use on the outside. It is found, however, that the same horse-power is not always developed on each side or the engine, which is an objectionable feature. The obvious way out of these difficulties is to increase the number of cylinders, so that their diameters are reduced, and also the arrangement is symmetrical ; thus three and four cylinder engines result. Compounding of locomotive cylinders is a vexed question, and it is still unsettled whether there is really anything to gain by it. In the light of recent experience on the L. & N.W.R. it would appear that there is not, while the success of the Smith compounds on the Midland Railway points the opposite way.

The object in compound engines is to get a prolonged expansion of the steam. This can be done in the case of a simple engine with large cylinders and a short cut-off ; but as the cylinders are double acting, boiler steam is alternately supplied at either end, while the opposite end is exhausting. There is considerable difference in temperature of the steam at admission and exhaust, and as the cylinder walls are at a mean between the two, condensation takes place at admission, and re-evaporation at exhaust. In addition to this, owing to the short cut-off, the port opening to steam is very restricted, producing wire drawing. In compound engines, the high pressure cylinders are smaller, consequently for the same horse-power the cut-off is longer, giving larger port opening, also the difference in temperature between steam at admission and exhaust is less ; consequently there is less initial condensation in the high pressure cylinder, and what there is is re-evaporated and passes to the receiver, where it is supplied to the low pressure cylinder. Initial condensation and re-evaporation occur here again, but the steam lost this way is only half what it was with the simple engine for the same degree of expansion. With simple engines the introduction of piston valves has given a larger area of port opening at short cut-offs , also less horse-power is expended on the valve gear, as the travel is less than in a compound, and with high piston speeds the condensation must be reduced ; also the heat generated by the friction of the piston rings on the walls of the cylinders must go towards increasing their mean temperature.

Whether there is any material gain effected by the principle of compounding is difficult to say. On one class of work the compound will give better results, and on another class of work the advantage will be with the simple engine.

There seems to be a prevailing opinion that any superiority of three or four cylinder compounds is due more to the better mechanical arrangement of the parts than to the actual compounding, but this does not apply to tandem or Vauclain compounds for obvious reasons (see Fig 1). With other compounds, owing to the larger surfaces and reduced pressures, wear is greatly reduced and better balancing obtained, both of which help to keep the cost of repairs down.

Latest British locomotive practice would confirm the view that the superiority of the compound type is mechanical rather than thermal, as three and four-cylinder simple engines are now running, and more are being built, but time has yet to show whether they are more economical than two-cylinder engines.

The Comparison of Two, Three and Four-Cylinder Engines.—*First Cost.* – The saving in coal and repairs due to the increased efficiency of the engine must be more than sufficient to balance the interest on the additional first cost of the engine and depreciation, also the greater oil consumption, before a three or four cylinder is a financial success over a two-cylinder engine, and this applies equally to the simple and compound types. In other words, a two-cylinder engine may burn more coal and cost more in repairs than a three or four-cylinder engine before the total costs are equal in each case. A three cylinder engine will be cheaper to build, and also will use less oil, than a four-cylinder.

Cylinder Surface. – For the same total piston area and the same stroke, the surface of cylinder walls and ends will increase with the number of cylinders used (Fig. 3). Thus a two cylinder engine has less surface than a three, and a three less than a four, with the result that condensation will be in approximately the same ratios. The cylinder surfaces in compound engines are larger than in the corresponding simple engines.

Balancing. – The effect of the different cylinder arrangements on the balancing of reciprocating parts is shown by Fig. 2. As mentioned before, the inside cylinder engine has smaller balance weights than the

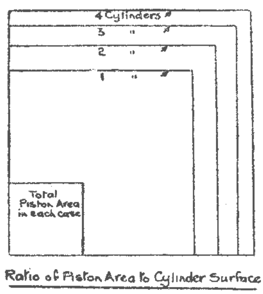


FIG. 3.

outside, so that the resultant producing hammer blow is much less. Three-cylinder engines are better than two cylinder outside, but not as good as two cylinder inside in this respect, and their superiority over the two-cylinder outside is mainly on account of the lighter reciprocating masses, and closer cylinder centres, as smaller cylinders are used. The four cylinder is by far the best, as the reciprocating masses on each side of the engine nearly balance one another, leaving only a small amount to be balanced in the wheel, thus the hammer blow on the rail at high speed is comparatively light. While on the subject of hammer blows it will be well to distinguish between those that throw extra loads on the rails only and those that affect bridges. With two-cylinder engines the resultant balance weight in the left hand wheel is nearly at right angles to that in the right hand, so that the additional load thrown on the sleeper will be the resultant of these two again, and will be about 1½ times the extra load on one of the rails. With three and four-cylinder engines the balance weights are nearly opposite one another. Thus when one is down the other is at the top of the wheel with the result that the load is increased on one rail and decreased an equal amount on

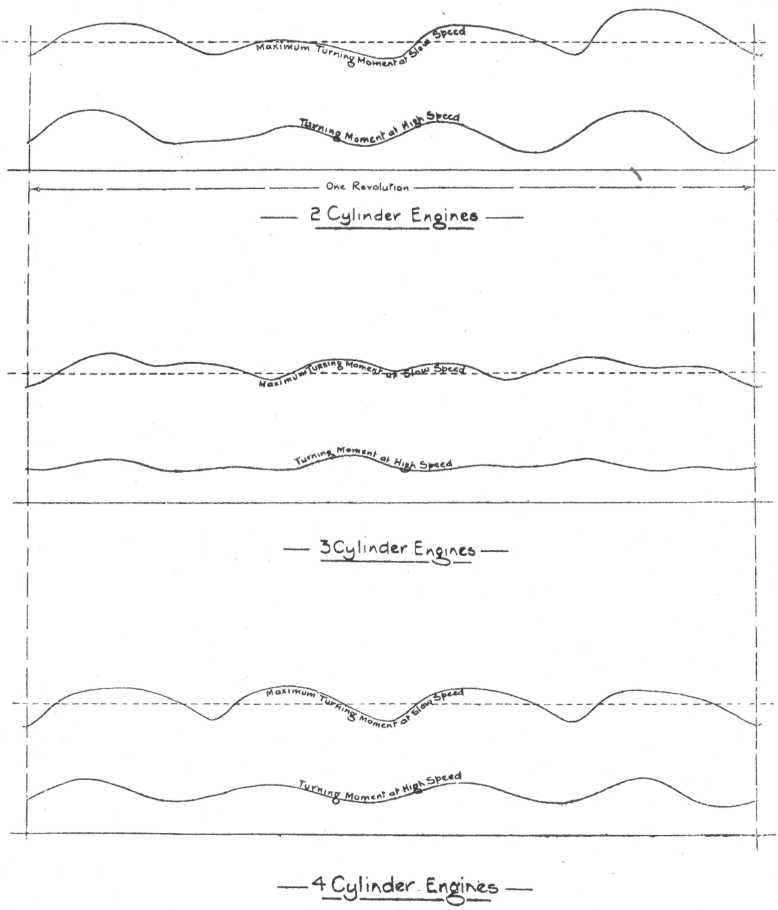


FIG. 4.

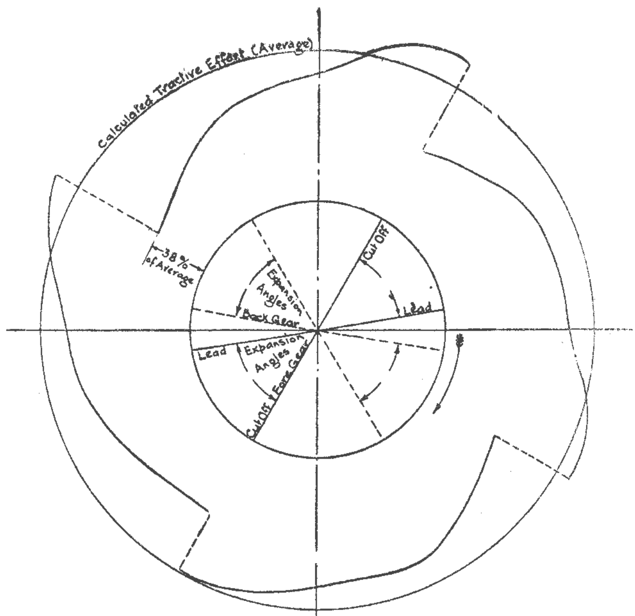
the other. Therefore there is no additional weight on the sleeper, and consequently none on bridges, as in the case of two-cylinder engines, only the rails themselves being affected.

Turning Moment. – The reciprocating motion of the piston is transformed into rotating motion at the crank pin, but the turning moment produced by the steam pressure varies throughout the stroke. At the ends of the stroke the piston is exerting no turning moment on the crank, but about half way it exerts the maximum, so that as the piston moves from one end of the cylinder to the other the turning moment starts from zero, rises to a maximum, and returns to zero at the other end. Thus, with only one cylinder, there are two periods in the stroke when no turning moment is produced ; so at least two cylinders must be used, the cranks being at right angles. By this means one cylinder is producing its maximum, while the other is exerting no turning moment. The resultant produced still fluctuates, but not to any serious extent. In the case of an engine with no cut-off and very long connecting rods the curve of turning moments would be the combination of two harmonic curves a quarter of a revolution apart. In practice, owing to the connecting rods being comparatively short, and also the fact that steam is cut off at some portion of the stroke, not usually exceeding three-quarter, the curve produced is distorted from its ideal shape, and this is shown by Fig. 4. The top curve is produced by slow speed, three-quarter cut off, and maximum load. At high speed the cut-off is very much shorter, so that as the piston moves from one end to the other, the steam pressure decreases rapidly, and at exhaust is only a fraction of the pressure at admission. The consequence is that the piston would produce a very irregular turning moment if it were not for the inertia of the reciprocating parts, which must be taken into consideration. These have no velocity at the ends of the stroke, but have a velocity equal to the crank pin about mid-stroke, so that a portion of the piston pressure is taken up in accelerating these parts up to the crank velocity, after which they give up this energy in slowing down in the other half of the stroke. The effective pressure on the crank pin is, then, less than the piston pressure at the beginning of the stroke, and greater than it at the end. The inertia at each end is about equivalent to a steam pressure of 40 or 50lbs per square inch at 60 miles per hour, which must be subtracted from the steam pressure at the beginning, and is added at the end of the stroke, the nett result being a fairly even pressure on the crank pin, although the steam pressure varies so greatly. This is illustrated by the lower curve. The four-cylinder engine gives curves similar to the two-cylinder, but they are more regular, as the distortion produced by short connecting rods is neutralized on each side of the engine, the cranks being opposite one another. The most even turning moment is produced by the three-cylinder engine, with cranks set at 120°, consequently the draw bar pull is always very uniform, and is no doubt more efficient. As the turning moment fluctuates less from the average, it can be greater for the same adhesion than in the case of the other two, in other words, slipping not being so liable to occur, the acceleration of the train can be greater for the same adhesive weight.

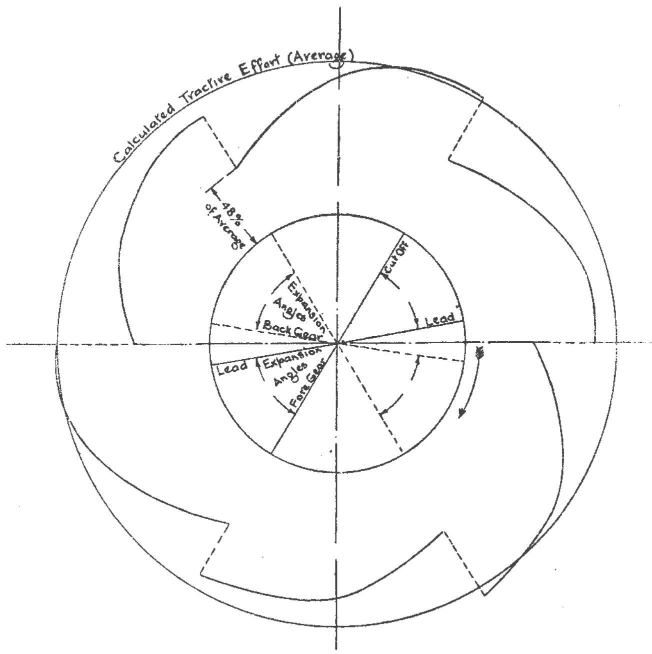
Dead Centres. – Another point in starting trains from rest is the liability of an engine to be on one of its " dead centres." It is commonly supposed by this that the engine is exerting no tractive effort ; as a matter of fact it is, but the pull is only a fraction of the maximum. If the train is standing on an up gradient or a curve, so that a large tractive effort is required to start, the engine will not be equal to it should it be on a " dead centre," but must be reversed to bring the cranks round to a more favourable position. The cause of these " dead centres " is due to the valve cutting off steam about three quarters of the stroke in full gear. Should the engine stop in such a position that cut-off has just taken place in one cylinder, the effective crank arm or leverage upon which the other cylinder acts is so short that only a fraction of the maximum turning moment is obtained, and this in two cylinder engines is about three-eighths of the average, and occurs four times in one revolution (Fig. 5). Very similar results are obtained from four-cylinder engines, but with three-cylinder engines there are six of these " dead centres " in a revolution, but the minimum tractive effort is greater than in the case of the other two, being nearly half the average.

Lubrication. – One of the disadvantages from the use of more than two cylinders is the increased quantity of oil necessary ; this will again be more in the case of the four than three-cylinder engines.

Breakdowns. – The liability of a breakdown with an engine will naturally increase with the number of parts, not only because there is more chance of a failure, but also because the driver cannot give as much attention to each detail, and the duty of properly oiling and inspecting his engine becomes a longer and a much more hurried process during a short stop. There are more parts to overheat, but the fact that the pressures are distributed over larger areas decreases the liability of overheating. An actual breakdown will usually be worse m the case of a four-cylinder



Dead Centres in 2 Cyl^r Engines



Dead Centres in 3 Cyl^r Engines

Fig. 5.

engine than a two ; for instance, in the event of a coupling-rod failing in a two-cylinder engine, it can be run at moderate speeds as a single wheeler without loss of power : the same failure in a four-cylinder engine would mean disconnecting the outside valve rods as well, so that the engine would run as a single wheeler with only two small cylinders, and could only continue with a very light train.

Repairs. – Repairs to an engine may be divided into two classes : those that may be performed while the engine is in the shed, such as closing up connecting rod " big ends " or making joints, and those that require stopping the engine from service, either a short time, such as changing wheels, or for a longer period, such as general repairs. It is natural to expect four-cylinder engines to need more repairs of the first kind, but it seems an established fact that they require fewer repairs of the second kind than two-cylinder engines. The heavier repairs not only involve the fitter's time, but the engine ceases to be earning money while laid up in the shed or shops.

Smokebox action. – In a two-cylinder engine there are four exhausts per revolution, and with a four-cylinder there are eight, but as they come in pairs, the effect on the fire is practically the same as a two-cylinder. With three-cylinder engines there are six exhausts, so that the vacuum obtained in the smokebox is more regular, and consequently the fire is less disturbed when pulling hard, thus economising fuel and reducing spark throwing and the claims for damage to property which so often result.

Priming. – The same state of things applies to the admission of steam as the exhaust. With two-cylinder engines there are four admissions per revolution, and with four-cylinder engines eight, which occur in pairs producing the same effect, and in three-cylinder engines six : consequently the supply of steam from the boiler is more regular in the case of the latter than the two former, so that when working hard there is less liability to priming, and a drier supply of steam is the result.

The Efficiency of the Engine. – In a two-cylinder engine the number of parts are reduced to a minimum, as also is the friction. A four-cylinder engine has nearly double the parts, and the losses due to friction will be increased. With regard to the valves, nearly double the power will be absorbed in working them, and this is considerable should they be flat slide valves. Piston valves will not absorb the same amount of mechanical energy, but it must be remembered that there will probably be a double leakage of boiler steam into the exhaust, and losses may occur this way. Against this is the increase in mechanical efficiency due to better balancing, and smooth riding of the engine at high speeds, which also reduces tyre wear both on the flange and the tread of the wheel.

Coupling Rods. – The arrangement of cylinders will affect the coupling rods to some extent. The throw can be reduced to a minimum only in inside cylinder engines. As three and four-cylinder engines have outside cylinders, the throw must be equal to half the stroke unless the crank pin is turned eccentric, but this can only be done to a small extent. Where the outside cylinders drive one axle and the inside another, the coupling rod between these two wheels does little else but maintain the relative position of the wheels to one another, and rarely transmits much power. In three-cylinder engines the outside cranks are at 120° to one another instead of 90° as in all other engines, and when one coupling rod is in line with the wheel centres, the opposite one produces all the turning moment in the other coupled wheel, but the crank pins not being at right angles, the effective crank arm is less than the actual throw, so that the load in the rod tending to produce buckling is greater than if the cranks were at 90° to one another.

Concluding Remarks. – In reviewing the previous statements, firstly as to the question of inside *versus* outside cylinders. In two-cylinder engines it must be said that whatever advantage the former possess, other considerations make it necessary to adopt outside cylinders where-ever great locomotive power is required, either for hauling fast and heavy expresses or long goods trains.

The question next arises whether this can be more economically performed by two, three, or four-cylinder engines. As far as modern British locomotive practice goes, compounding may be left out of the question, as it is not viewed with much favour in this country, where simplicity of design and working are so much considered. The great disadvantage of two-cylinder engines for express work is the heavy hammer blow on the rails produced by balancing, or rather partially balancing, the reciprocating parts. It is true this weight may be spread amongst the coupled wheels, and in this case the hammer blow in each wheel of an Atlantic type engine is greater than with a six wheel coupled ;

still, the total hammer blow remains, and the load due to this is added to the maximum wheel load of 20 tons per axle which some railways allow. The consequence is that bridges and other expensive permanent way works are supporting loads greater than they were originally designed for, so these have to be strengthened or replaced. If four-cylinder engines were used exclusively on fast passenger work, the upkeep and renewals to the whole permanent way would be reduced, and although the locomotive department might not gain or even lose by it, the railway as a whole would profit through the engineering department.

In other branches of traffic – passenger trains on hilly roads, heavy goods, and suburban work – the three-cylinder engine should excel. The hammer blow is not great where the speed is moderate, but still it is lighter in a three-cylinder than the two. Further, the three-cylinder engine starts better, giving very uniform draw bar pull, and makes better use of its adhesive weight than the other engines, a point which is invaluable in suburban work. With heavy loads the smokebox action is much better, and in climbing banks there is not the same liability to throw sparks, while the even draw bar pull minimises slipping, and there is not so much danger of priming. The three-cylinder engine costs more to build than the two, but not so much as the four ; the crank axle is not such a source of weakness, as it is only a single throw, and, if balanced to prevent the load due to centrifugal force, should have a long life. It is cheaper to renew, in any case, than a two-throw crank.

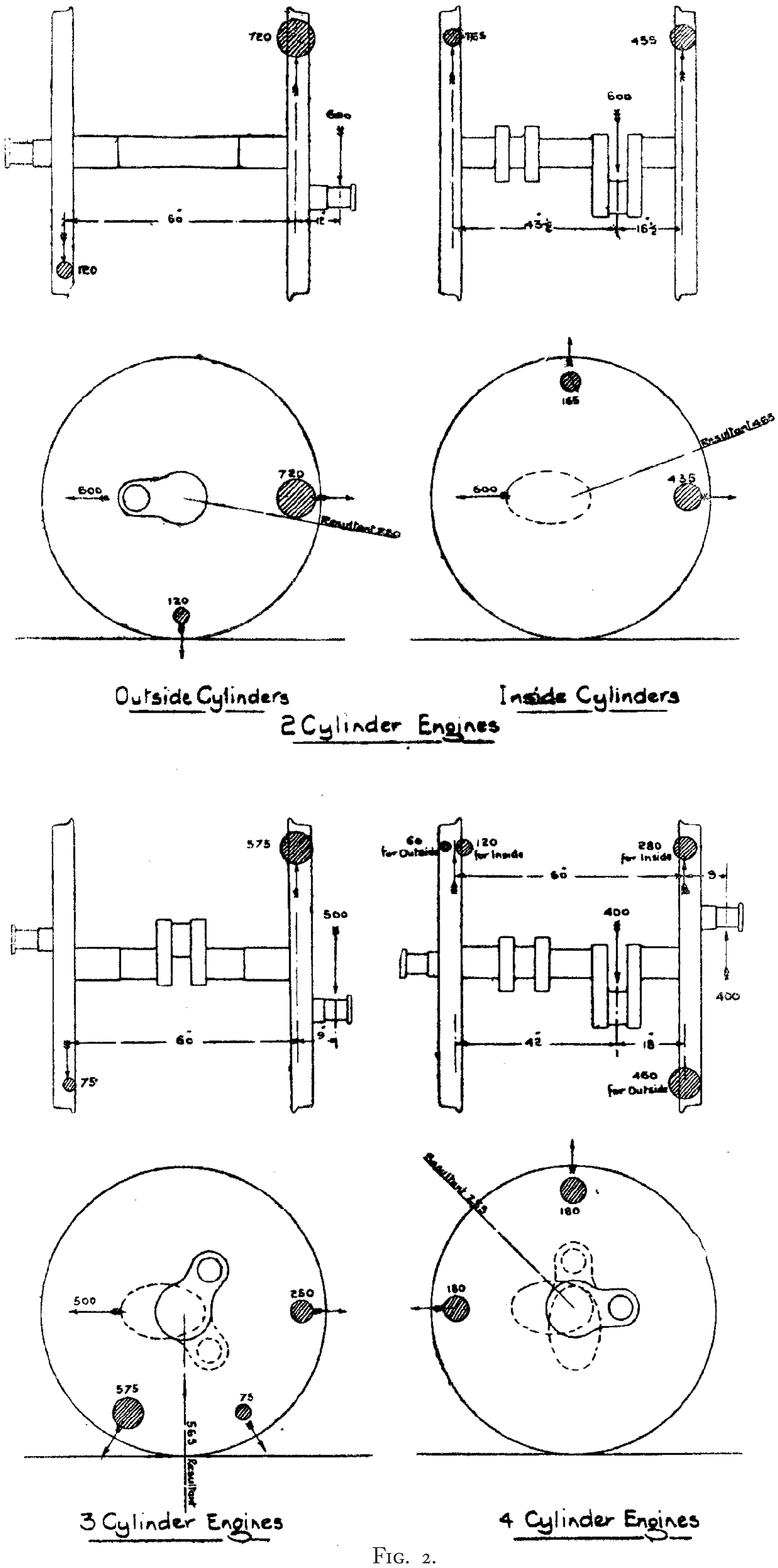

Outside Cylinders
Inside Cylinders
2 Cylinder Engines
3 Cylinder Engines
4 Cylinder Engines
Resultant 280
Resultant 485
Resultant 563
Resultant 283
for Inside
for Outside

FIG. 2.