(*Paper No. 3198.*)

"The Tocopilla Railway."

By Robert Stirling, M. Inst. C.E.

The Tocopilla Mountain Railway was built to open up the extensive nitrate-of-soda deposits of Toco, Chili, a continuation to the south of the famous nitrate fields of Tarapaca. It is of 3 feet 6 inches gauge, with exceptionally sharp curves, and the design was made with a view to employing the heaviest type of rolling stock possible, for the most economical handling of the traffic on the heavy gradients. Of all the railways on the west coast of South America which climb the coast range of the Andes, it is by far the boldest and most difficult, owing to the rugged nature of the mountains, which there rise almost out of the sea, and are cut only by a ravine too steep and crooked to be available for a railway.

Starting from the port of Tocopilla, the line rises with continuous gradients, varying between 1 in 24·4 and 1 in 66·7, to a height of 4,902 feet above sea-level at mile 34, and thence falls with a steady gradient of 1 in 66·7 to 3,631 feet, at mile 54. Here is the station of Toco on the level of the nitrate grounds, whence branches run to the different nitrate works.

The line, *Fig. 1*, is divided by the ruling gradients into four sections, and attention to this feature has aided greatly in economical working. The first section is from the port to Barriles at mile 17, with a practically uniform gradient of 1 in 25 (maximum 1 in 24·4), and almost continuous curves, many of them of only 181 feet radius. The second section, 9 miles to "Central" Station at mile 26, has gradients averaging 1 in 37, but easy curves of not less than 500 feet radius. The third section, of 28 miles, rises 8 miles to the summit, and falls 20 miles with a uniform gradient of 1 in 66·7 to Toco at mile 54, also with easy curves; and the fourth section from Toco to the five nitrate works already established, in all about 17 miles, has easy gradients and curves on the main line, but sharp curves and steep gradients on the sidings within the works.

The first section of 17 miles alone presents difficulties in construction or working, and is the only one that need be particularly described. Starting with a reverse just outside the station at Tocopilla, the line begins at once to climb the hillside parallel with the sea-shore to mile 4, where there is another reverse, at 796 feet above sea-level. Returning directly above this line for over a mile, it then begins winding on the sides of almost perpendicular hills, in and out of the side gulleys, high above the bed of the main ravine, with almost continuous rock-cuttings and curves, to mile 15. There it reaches the level of the main ravine, which has opened out to a valley, and continues in it for the remaining 2 miles with slightly easier gradients and curves.

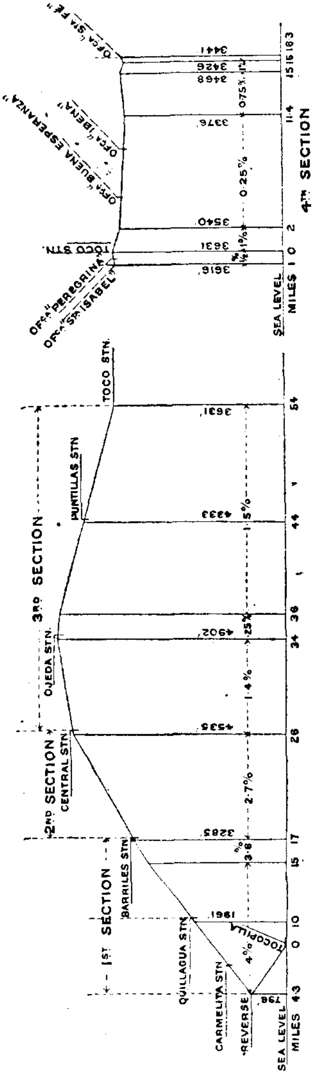


Fig. 1.

Horizontal scale, 1 inch = 16 miles. Vertical scale, 1 inch = 4,000 feet.

The curves on this section, and the proportion they bear to the total length of 17 miles, are approximately shown in Table I.

Several of the sharpest curves are through more than a semicircle, and between very many of the curves there is only 24 feet of straight line. By adopting such sharp curves bridges were altogether avoided, and only one short tunnel was required; and the saving in cost was very considerable, as compared with minimum curves of even 250 feet radius. This would no doubt have been saved many times over in the working-expenses, for the sharp curves on this section add seriously to the cost of working the railway; but money was scarce, and the railway had to be built within a certain sum or not at all; while in view of the heavy traffic which will have eventually to be carried when the district is fully opened up, it was not advisable to reduce the gauge.

The greatest care has to be taken to keep the curves in shape for the passage of the heavy locomotives and cars, and the side wear of the outside rails on the curves is excessive, as will be seen from *Fig. 4.* The line is laid with rails of only 40 lbs. per yard, but these are being replaced on the gradients by rails of 48 lbs. per yard.

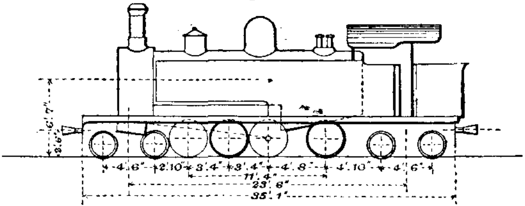
The gauge on curves is ½ inch wide, and the rails are kept in gauge by tie-bars catching the flange of the rail, so as not to weaken the section by drilling, and by double spikes on the outside rail. Latterly also sole-plates have been used, under the outside rail, on every alternate sleeper. The sole-plates as originally supplied had to be slipped over the ends of the rails, and were found so inconvenient that they were almost discarded. However, by altering them slightly they have been used with good effect, as each takes four spikes well distributed in the sleeper. The spikes are of the ordinary pattern, $\frac{7}{16}$ inch square, and weighing 7 oz. each. The sleepers are of native Chilian woods, 7 feet by 8 inches by 4 inches, and in the rainless climate will last easily twenty years or more; except on the curves, where the frequent re-spiking reduces the life to about six years.

TABLE I.

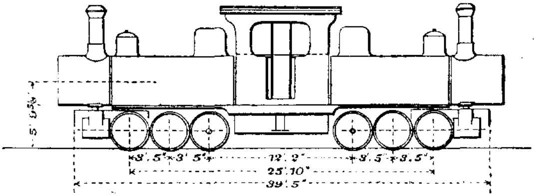
Radii of Curves.	Number of Curves.	Total length.	Per Cent. of Total 17 Miles.
Feet.		Yards.	
181	37	4,128	13·8
Between 181 and 250	79	6,888	23·0
„ 250 „ 300	31	3,016	10·1
„ 300 „ 400	35	3,048	10·2
„ 400 „ 600	31	3,232	10·8
over 600	35	1,088	3·6
Total curves . . .	248	21,400	71·5
„ straight . . .	..	8,520	28·5
Total . . .	..	29,920 = 17 miles	

The superelevation of the outer rail on all the curves under 300 feet radius is fixed at 3½ inches, but on the short curves even this cannot be obtained, because, to suit some of the heavy single locomotives, the elevation has to be increased very gradually, and not more than 1 inch in 24 feet. While it requires one man to ⅔ mile to keep this section in repair, the other sections only require one man to more than 2 miles, or, in other words, just as many men are needed to keep this 17 miles in repair as for the remaining 54 miles of line.

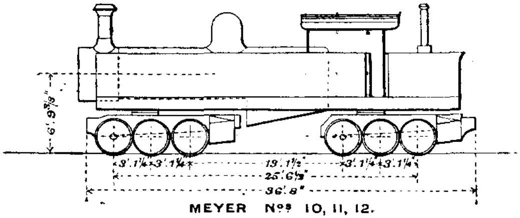
Figs. 2.



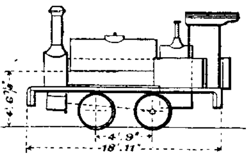
8 WHEELED COUPLED. Nos 1, 2, 4.



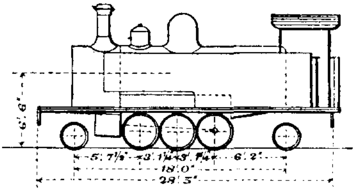
FAIRLIE Nos 8, 9.



MEYER Nos 10, 11, 12.



4 COUPLED SHUNTER. Nos 6, 7.



6 COUPLED SHUNTER. Nos 13, 14, 15.

The different classes of locomotives in use are shown in Table II and *Figs. 2.*

The eight-coupled single locomotives were originally intended to do the work on all the sections of the line, but, although designed to be extremely flexible for engines of this class, they

TABLE II.

Class.	Weights.		Diameter of Wheels.		Cylinders. Diameter and Stroke.	Boiler.									Tank Capacity.		Train-Load on Gradient of 1 in 25 excluding Locomotive.
						Internal Diameter of Barrel.	Heating Surface.			Tubes.			Area of Grate.	Pressure Lbs. per Square Inch.			
	Total Weight.	Weight on Drivers.	Drivers.	Bogie.			Firebox.	Tubes.	Total.	External Diameter.	Length.	Number.			Coal.	Water.	
	Tons.	Tons.	Ft. Ins.	Ft. Ins.	Ins. Ins.	Ft. Ins.	Sq. Ft.	Sq. Ft.	Sq. Ft.	Inches.	Ft. Ins.		Sq. Ft.		Tons.	Gals.	Tons.
8-coupled, Nos. 1, 2, 4.	51·75	34	3 2½	2 0½	2 17 × 21	4 3	93·15	881·65	974·8	1¾	11 2⅞	174	16	160	2	2,070	65
4-coupled, shunter, Nos. 6, 7.	16	16	2 10¾	..	2 10½ × 16	2 7	31·9	271·5	303·4	2	8 4½	64	5	140	0·37	350	20
Fairlie, Nos. 8, 9.	57	57	3 0	..	4 14 × 20	3 5½	38·4 38·4 76·8	573·8 573·8 1147·6	612·2 612·2 1224·4	1¾	10 8½	117 117 234	9·65 9·65 19·3	160	2	1,700	120
Meyer, Nos. 10, 11, 12.	53·5	53·5	2 10¾	..	4 14 × 18	4 4	104	1069	1173	1¾	11 3$\frac{1}{16}$	211	24·1	160	3	2,000	120
6-coupled, shunter, Nos. 13, 14, 15.	37	27	2 10¾	2 0½	2 14 × 18	3 9	62	574	636	1¾	9 11½	128	11·2	160	1·47	1,000	50

were found impracticable on the sharp curves, owing to too great rigidity causing excessive wear of tire-flanges. They are now used on the other sections where curves are easy, and there do excellent work.

"Fairlie" engines were then installed for use on the first section, but have been superseded by "Meyer" single-boiler engines. These were built in 1893, and are the first locomotives of this class built in England. They were suggested by the Author after studying the working of "Fairlie" engines on the "nitrate railways" of Tarapaca during 1887–89.

In designing these locomotives the problem was to improve on the "Fairlie," while keeping the maximum weight per axle to 9 tons. This admitted of an engine weighing 54 tons, and to make full use of this adhesive weight boiler and cylinders in proportion had to be provided, and a capacity of 2,000 gallons of water and 3 tons of coal. Table III shows the performance of these three classes on the first section, taken from actual working:—

TABLE III.

Class.	Total Weight.	Weight on Driving Wheels.	Net Weight of Train.	Lbs. of Coal per Pulling Mile.
	Tons.	Tons.	Tons.	
8 coupled single	51¾	34	65	160
"Fairlie"	57	57	120	272
"Meyer"	54	54	120	210

The above results were obtained with patent fuel; but coal is cheaper and more convenient to use, and with it the advantage is still more in favour of the "Meyer" type, owing to the larger grate-area of which the design admits.

The six-coupled single engines were designed at the same time for the heavy shunting work between the mole and the station in Tocopilla, where the gradient is 1 in 25, and the 181-foot curves are numerous. They are also well adapted for the traffic between the nitrate works, for although the main line is free from sharp curves and gradients, yet in the sidings within the works both are found. The wheels and motion are interchangeable with the engines of the "Meyer" class.

The various classes of cars in use are shown in *Figs. 3* and Table IV. The original cars were wooden and weighed 5·6 tons to carry 12 tons, but by slight alterations they were made to carry 15 tons.

Next the steel cars were designed, with channel-section steel frames and corrugated-steel sides, weighing 5·5 tons, and carrying 20 tons. This gives the exceedingly good ratio of paying load to dead weight of 3·6 to 1. A number of high-sided cars are required to carry coal in bulk, but these weigh only a trifle more, 5·7 tons. A few tubular cars are being experimented with, but show no advantage in weight, and have nothing to recommend them. This low weight of cars has not been obtained at the expense of efficiency, for every part is of ample strength. The weights given include automatic vacuum-brake fittings, which add 537 lbs. to the weight of the car. Centre buffers are used with hooks, the slack being taken up by an eccentric gear. All have oil axle-boxes of the latest pattern.

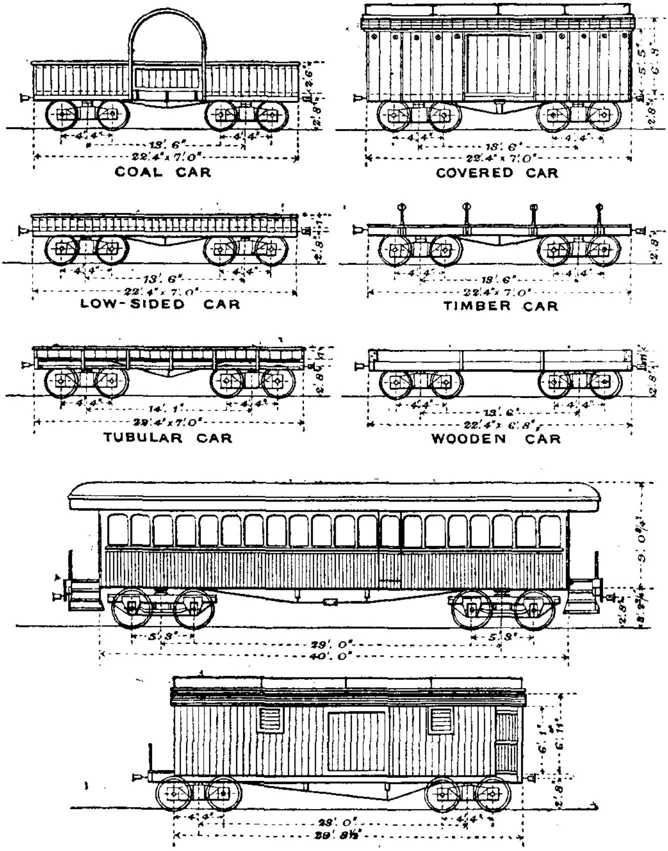
The rolling stock is fitted throughout with automatic vacuum-brakes as well as hand-brakes and cast-iron brake-blocks; 18-inch cylinders are used on the steel cars, so as to get the requisite power without too fine adjustment of brake-blocks or dependence on a high vacuum. The gear is designed so that a vacuum of 12 inches is sufficient to control a train on the 1 in 25 gradients.

TABLE IV.

—	Weights.					Capacity.	Diameter of the Air-Brake Cylinder.
	Car Empty.	Net.		Total Weight with			
		Coal.	Nitrate.	Coal.	Nitrate.		
	English Tons.	English Tons.	English Tons.	English Tons.	English Tons.	Cubic Feet.	Inches.
Coal car . . .	5·70	12	20	17·70	25·70	390·83	18
Low-sided car .	5·50	5	20	10·50	25·50	156·33	18
Covered car . .	7·93	..	20	..	27·93	847·33	18
Timber car . .	6·16	..	20	..	26·16	..	18
Tubular car . .	5·74	5	20	10·74	25·74	156·33	18
Wooden car . .	5·60	5	15	10·60	20·60	134·69	15
Passenger car .	13·00	..	..	..	..	..	18
„ „ .	..	..	..	..	..	1248·00	18

The water-supply has been a serious item in the cost of construction of the railway, and is in the working expenses. The country through which the line passes is absolutely devoid of fresh water, and all the water has to be distilled from the sea at the port or from the brackish water of the River Loa, 3 miles beyond Toco Station. The water of the Loa is almost equivalent to sea-water diluted ten times, and contains 245 grains of solid matter per gallon, 156 grains being sodium chloride. An attempt to use it in the locomotives during more than a year showed that the train-load had to be reduced 25 per cent. on account of priming, and the corrosive action was such that the direct stays of the fire-box crowns, of iron $1\frac{1}{8}$ inch in diameter, were reduced in that time to $\frac{1}{2}$ inch in diameter next the copper plate. No system of purification was feasible, for although the lime could have been removed and the corrosive qualities could have been counteracted, the sodium chloride would still have remained to cause priming, with the consequent reduction of train-load.

Figs. 3.



Two distilling plants were accordingly erected, one at the Port, and the other at the Loa, each with a capacity of 24,000 gallons per day. These are both sextuple-effect apparatus with six evaporators under an ultimate vacuum of 26 inches, and using salt water in

Lancashire boilers. The corrosive effects of distilled water are neutralized by adding lime in solution, and the proper proportion has been found by experience to be about 1 lb. of quicklime per 1,000 gallons of distilled water. From the port, part of the water is pumped through about 6 miles of 3-inch steel piping to the water-station at mile 10 at a height of 1,970 feet above sea-level, the pressure at the pumps being 900 lbs. per square inch.

From the Loa all the water produced is forced through 4-inch steel piping to the summit station of the railway, a distance of 23 miles, and 1,550 feet above the level of the pumps. Tanks of 6,000 gallons capacity at two intermediate stations are supplied from the pipe-line by valves $\frac{5}{16}$ inch and $\frac{3}{8}$ inch in diameter, regulated by hand, and at the summit there is a reservoir tank of 50,000 gallons capacity.

The railway is supplied with water by pipe-lines from either end, leaving a section from mile 10 to mile 34 to be supplied by car-tanks run down from the summit. The quantity used on this section is made comparatively small by arranging, as far as possible, for the down locomotives to fill their tanks at the summit to take them back, and by returning the double engines to the port from mile 17 with empty tanks. The original scheme was to supply the whole line and the port with river-water, but the impossibility of making it usable by any process of purification short of distillation caused this plan to be abandoned.

The cargo carried by the railway consists almost exclusively of coal, forage, and merchandise taken "up," and nitrate of soda brought "down." The "up" traffic is only about 25 per cent. of the total, and this distribution contributes very materially in reducing the cost of carriage, which under so many natural difficulties must necessarily be very high. Coal forms by far the larger portion of the "up" cargo, and high-sided coal-cars only load 12 tons and low-sided only 5 tons, while nitrate in bags is loaded 20 tons on a car. Notwithstanding this difference there is a good deal of empty "up" traffic, but all cars are fully loaded "down." The total traffic in 1898 was nearly 200,000 tons.

In working the traffic the advantage and economy of the steady gradients on each section is at once apparent. In starting from the port a "Meyer" or "Fairlie" locomotive is loaded regularly with a train of 115 tons to 125 tons, exclusive of the weight of the locomotive, and with this load is working steadily at 30 per cent. cut off, or to nearly its full power. With a dry rail a train of 135 tons can be taken up, but the lighter load is found to be more economical. The distance of 17 miles to Barriles is covered in

2½ hours, including 15 minutes for two stops to take water at miles 7 and 10. The "up" trains average eight to nine cars between loaded and empty, but may vary between six cars and fifteen cars to make up the load, depending on the cargo to be taken up and the number of empty cars required to bring down nitrate. The "down" journey is strictly timed to 2 hours for the 17 miles, which keeps the speed so that the train is always thoroughly under control on the sharp curves.

On the second section an eight-coupled single engine takes the load the double engine has brought up and one or two empty water-tanks, weighing about 9 tons each, covering the 9 miles in 1 hour.

For the third section the same engine takes two trains to the summit and down to Toco, 28 miles in 1¾ hour. On the "down" journey from Toco the load for these engines is twelve cars loaded with nitrate, making a train of 270 tons. This train is taken 20 miles on an up gradient of 1 in 66·7 and 8 miles on a falling gradient of the same amount to "Central" Station (mile 26) in 2½ hours, including two stops for water. By arranging the traffic in this way a locomotive on an up grade is always working to its full capacity or maximum earning power. From "Central" down to the port the loads are arranged so that a train is never less than four cars, to help to brake the locomotive down, and as nearly as possible an equal train for each engine.

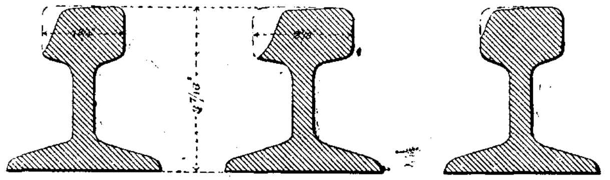
The real difficulties under which a railway of this class must be worked arise entirely from the sharp curves, for the heavy gradients, with the correspondingly heavy consumption of coal and water, and the absence of a natural water-supply, entailing the cost of distilling and pumping, can hardly be regarded as peculiar to any one railway. All that can be done is to pay especial attention to the consumption of coal and water by the locomotives, and to cheapen as much as possible the cost of distilling and pumping. These nevertheless form serious items of the cost of working, water representing 12 per cent. and coal 16 per cent. of the total working-costs of the railway. The division of the working-expenses of this railway is interesting for comparison with an ordinary railway.

		Per Cent.
Permanent way (maintenance and renewals of line, &c.) . . .		15
Locomotive department, running expenses (wages, coal, &c.) .	39	
,, ,, repairs to engines and cars . . .	21	
	—	60
Traffic and telegraph (station and train wages, lighting, &c.) . .		12
General (management, offices, taxes, &c.)		13
		100

The curves are the cause of a very appreciable part of the heavy consumption of coal and water, for the resistance due to them is equivalent to an additional height of 440 feet, or about 8 per cent. of the total height to the summit of the line. The gradient on the long curves of 181 feet radius is reduced from 1 in 25 to 1 in 33·3. Recognized formulas call for rather more than this, but it is very clearly shown in working that at the low speeds this is ample compensation for the increased resistance to the train on the curve. When a train is climbing the gradients at a speed of 10 miles per hour, if the regulator valve of the locomotive be kept in the same position, the speed of the train slightly increases as soon as it comes on an almost straight part of the line, and the same happens in like degree when it gets on one of the long curves of 181 feet radius with the gradient reduced 1 per cent. But the real difficulties due to the sharp curves are the wear of rails and tire-flanges, thereby adding 50 per cent. to the cost of maintenance of permanent way and repairs to rolling stock, or, say, a total of 8·4 per cent. of the total working-expenses. The sections of worn rails and tires show that this may well be *Figs. 4* and *5*. These were taken by plaster casts from worn rails and tires.

In *Figs. 4* No. 1 shows one of the original 40-lb. rails taken from the outside of a curve of 181 feet radius after the passage of about 71,706 wheels. When the wear has reached this stage the flanges of the wheels begin to cut the fish-plates, and the rails have to be renewed. Section No. 2 is of a 48-lb. rail, and with the wider head allows of double the amount of metal being worn away before the wheel flanges strike the fish-plates and the rail has to be renewed. Supposing the rails were of the same quality of steel, this would give double the life of the 40-lb. rails; but the 48-lb. rails proved to be much softer, and of the two lots of 48-lb. rails the harder gave a life of only 71,706 wheels for the loss of double the weight of metal, while the softer only gave 62,642 wheels' life

Figs. 4.



No. 1.—40 lbs. per yard. No. 2.—48 lbs. per yard. No. 3.—40 lbs. per yard.

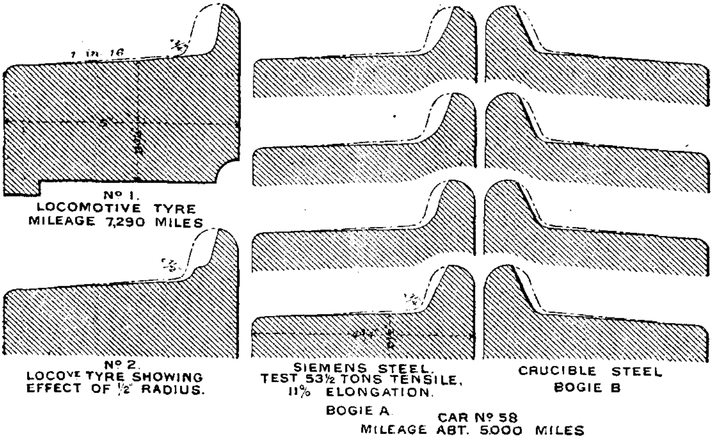
Scale, ¼ inch = 1 inch.

for the same wear. There was no appreciable loss in adhesion on the harder rails, although this has been advanced as a reason for using softer steel.

Section No. 3 is from one of the 40-lb. rails, originally laid on a curve of 302 feet radius, after 9 years' service, or, say, the passage of 550,000 wheels. This shows very clearly how little trouble there would have been had this been the minimum curve on the line.

In the wheel-tires, *Figs. 5*, the effect of the quality of the steel is even more marked. The section of locomotive-tire shows the template to which it has been found best to turn the tires, and the limit to which the flanges are allowed to wear before being re-turned. The radius at the root of the flange has been gradually reduced from 1 inch to ¼ inch. With the larger radii the wheel, particularly on the bogies of engines and cars with light loads, was apt to climb the rail, and wear a groove, as shown in section No. 2, reducing the depth of the flange, and in aggravated cases causing derailment. To get a new flange ⅝ inch to ¾ inch must be turned off, so that a tire 2¾ inches thick can only be re-turned twice. It is found much more economical to run the flanges to this stage, as by far the greater part of the cost of re-turning consists, not in the loss of metal of the tire, nor in the actual work in the turning-lathe, but in the work entailed in taking the wheels from, and returning them to, the locomotives and cars, and

Figs. 5.



Scale, ¼ inch = 1 inch.

the withdrawal of these from the traffic during the operation, while the mileage is so short that very often no other part of the engine or car requires repairs. For each turning the mileage has varied on the same engine, "Fairlie" or "Meyer," between 500 miles and 17,000 miles, depending on the quality of the steel of which the tire was made. The former mileage was from Siemens steel of ordinary hard quality to suit English practice, say 45 tons tensile, and the latter from crucible steel of a quality which the makers themselves have not been able to repeat. The analysis did not show anything very special, nor did the steel appear particularly hard in the turning-lathe, but in service the result was as stated. The nearest approach to this, until lately, has been in a special Siemens steel giving a test of 53 tons tensile and 11 per cent. elongation, which showed an average of 7,000 miles per turning. Lately tires of crucible steel of American manufacture have given regularly 12,000 miles per turning.

Car-tires of this same American brand of steel, and of Siemens steel giving the above special test, were put under the same car, and after 5,000 miles gave the sections shown. This shows very clearly how much depends on the quality of the steel, and how much is to be expected, when a quality such as that giving 17,000 miles can be obtained with certainty.

The railway was originally designed for lighter rolling stock—4-coupled "Fairlie" locomotives of 36 tons weight and bogie-cars carrying 10 tons—and there is no doubt that, had these types been adopted, the difficulties of rail- and flange-wear on the curves would have been avoided. However, it has been clearly proved that, taking into consideration the working of the whole railway, it is now more economical to have the present heavy rolling stock, notwithstanding the excessive wear of rails and tyres involved by the curves of the first section.

"Fairlie" or "Meyer" engines of the above weight for the working of the first section would have taken two-thirds the present loads, and 6-coupled engines, taking three-quarters the load of the present 8-coupled class, would have taken their place on the other sections, and the cars would have carried half the load of the present steel cars. Thus, about 50 per cent. more locomotives would have been required, each costing little less than the present heavier engines, and double the number of cars, each costing at least 75 per cent. of the cost of the present cars, and almost certainly giving a greater proportion of dead weight. With a 50 per cent. increase in the number of trains run, wages of train-personnel would have increased in like proportion, and more than neutralized the saving in permanent-way expenses due to less wear and tear of curves, while repairs to a greater number of locomotives and cars would have made the cost of maintenance of rolling stock as high as it now is for a less number, subjected to heavier flange wear. There would therefore have been an expenditure of 50 per cent. more capital in rolling stock, and no reduction whatever in working costs, but more probably an increase. This has been the gain so far due to the heavy rolling stock, and in the future the gain in reduced working-expenses will be clearly apparent.

By increasing the radius of the curves to a minimum of 300 feet the working-expenses would be at once reduced by the 8 per cent., which, as already stated, is the estimated extra working-cost due to the sharp curves, but this would entail an expenditure which would not be recouped in years by the economy obtained. Whereas, without extraordinary expenditure, by merely renewing the rails and tires as worn with a harder quality of steel, a reduction of 5 per cent. in the working expenses would be obtained in say 3 years, and the extraordinary expenditure on improving the curves can be undertaken as warranted by increased traffic, and will yield proportionately greater results.

It appears, therefore, after the experience gained on this railway, that a line with sharp curves can be equipped with relatively heavy rolling stock with economy in capital expenditure and in working-costs, and that, when an ultimate heavy traffic is expected for the railway, there is no question that this is the right policy. The curves can always be improved when the traffic warrants the expenditure, but light rolling stock, once adopted, must always interfere with economical working when the improved curves admit of heavier rolling stock, or, if replaced, will entail expenditure additional to that required for the improvement of the curves alone.

The line was designed by Mr. William Stirling, of Lima, Peru, and was opened for traffic in October, 1890.

The Paper is accompanied by three drawings, from which the Figures in the text have been prepared.