

November 21, 1876.

GEORGE ROBERT STEPHENSON, President,  
in the Chair.

No. 1,453.—“The Fracture of Railway Tires.” By WILLIAM  
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THE durability of the tires on the wheels of railway rolling stock is one of the most important questions for consideration, as owing to their failure many fatal accidents have occurred, only exceeded in number by those arising from collisions. Thus, in Great Britain, in 1874, the fracture of tires amounted to 55, occasioning the death of 37 passengers and an enormous pecuniary loss to the railway companies. In the twenty-seven years, 1847 to 1874 inclusive, 80 tire accidents were reported upon by the Board of Trade officials, which resulted in the loss of 74 lives and in 236 cases of more or less serious personal injury. Previous to 1872 the companies made no return of accidents from the fracture of tires; in that year the number of such accidents was 58, in 1873 it was 30, and in 1874, as before stated, 55. During these three years, however, only those failures which were attended by serious results were reported; but in 1875 every one was systematically recorded. The General Report of Captain Tyler for that year comprises no less than 684 tire failures; and though these resulted in no loss of life, they caused the derailment of several trains. The absence of fatal results is probably due to the great care now exercised in the examination of tires, most of the failures having been discovered at stations.

Various explanations of the cause of these fractures have been brought forward, with various degrees of apparent support from experience. Sometimes the cause has been clearly traceable to a defective weld or to obviously inferior material, at other times to a reduction of the sectional area of the tire by rivet or screw-holes. But when not assignable to these causes, the origin of the fracture has generally been obscure, and its explanation a matter of speculation.

So far as the Author is aware, the forces productive of the fracture of the tires of wheels running over smooth and rigid surfaces have never been satisfactorily investigated. His present object is to point out what seems to be an efficient cause in the

production of those strains which must exist in the material of tires prior to their fracture.

The actual cause of fracture, where that has been unexplained at the time of the accident, does not appear to have received much subsequent consideration, and the theories advanced to account for it seem to be untenable upon examination. But it is necessary here to consider some of them, beginning with that which attributes fracture to the strain put upon a tire, by shrinking it on a wheel having a slightly greater diameter than that of the inside of the tire before it is shrunk on. It has usually been assumed that this strain would produce an extension of the tire, equal to the difference in length of the circumference of the wheel body and that of the inside of the tire, before the latter is expanded by heating, for the purpose of being shrunk on to the rim of the wheel. In this assumption, however, the wheel, upon which the tire is shrunk, is considered to be perfectly rigid and unyielding; whereas, although it may be—with reference to ordinary considerations—assumed to be rigid, it is not absolutely so, and is, in fact, not so rigid as the tire. Therefore, supposing the resistance to compression and to tension to be equal in the rim of the wheel and in the tire respectively, the tensile strain thrown upon the latter cannot be more than one-half that calculated on the above assumption, for the work of eliminating the difference between the lengths of the tire and the rim is done, not upon the tire only, but through double its length, or through that of the tire and the rim together.

If a tire were shrunk on an absolutely rigid body whose circumference was somewhat greater than that of the inside of the tire, the strain upon the latter would undoubtedly be that necessary to produce an extension of its length equal to the above difference; but if the body be compressible, however little, the necessary extension will be reduced, and the strain also. Take, for example, a wheel body with a diameter of 3 feet, and a tire to be shrunk on it with a diameter of 2.995 feet, the difference in the circumferences being 0.1875 inch, and let the tire have a sectional area  $A = 10$  square inches, and the rim of the wheel an area  $a = 6$  square inches. Then the increment  $\lambda$  in the length of the tire and the decrement  $\lambda'$  in that of the wheel rim necessary to eliminate the above difference ( $0.1885 = \lambda + \lambda'$ ) in their respective lengths will be inversely as their areas, or

$$A :: a : \lambda' :: \lambda$$

$$\text{and} \quad \frac{\lambda + \lambda' \times A}{A + a} = \lambda' = 0.1178 \text{ inch}$$

$$\text{and} \quad \frac{\lambda + \lambda' \times a}{A + a} = \lambda = 0.0707 \quad ,$$

Taking a co-efficient of elasticity,  $C$ , = 27,000,000, the strain  $f$  and  $f'$  necessary to produce the above increment and decrement respectively will be

$$f = \frac{\lambda C}{l} = 16,906 \text{ lbs.} = 7.547 \text{ tons, which} \times A = 75.47 \text{ tons;}$$

$$\text{and } f' = \frac{\lambda' C}{l'} = 28,097 \text{ lbs.} = 12.543 \text{ tons, which} \times a = 75.26 \text{ tons;}$$

$l$  and  $l'$  being the original lengths of the tire and rim, the difference in which causes the above slight difference in  $f$  and  $f'$ ; but as this is eliminated, the strain on the tire and wheel rim will be practically

$$= \frac{75.47 + 75.26}{2} = 75.36 \text{ tons. Thus, if the breaking strain}$$

of the material of the tire be 25 tons per square inch, the above strain is less than one-third that necessary to produce fracture, leaving on the whole tire a marginal strength of 174.64 tons, even in the case of wheel rims of such large sectional area as that assumed. The radial component of the above circumferential strain on the tire will be that expressed by the relation between transmitted forces (by a curved surface) of tangential tension and radial compression. Lagrange's theorem,<sup>1</sup> is here applicable, and may be thus stated:—

Let  $R$  = radial compression due to  $T$ ;

$T$  = tangential tension;

$r$  and  $r'$  = two radii of principal curvature;

$$\text{then} \quad R = T \left( \frac{1}{r} + \frac{1}{r'} \right).$$

In the present application of the theorem, as the tire is circular

$$r = r', \text{ and the above equation becomes } R = \frac{2T}{r} = \frac{2 \times 75.36}{18} =$$

8.37 tons radial pressure per circumferential inch. With heavy

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<sup>1</sup> Vide "Traité de mécanique analytique, sec. 2 (statique), sur l'équilibre d'une surface flexible," &c., Paris, 1853. Also "Miller's Hydrostatics," Cambridge, 1831; and "Mallet on Volcanic Energy," &c., Phil. Trans., p. 173, 1873.

engine wheels these strains would probably be slightly increased, as the rim would be less free to alter its dimensions at the junction with the spokes. But between these, alteration may take place both by change of dimension and form. The resistance, however, to decrement in the length of the rim, and to the necessary radial compression resulting therefrom, is exceeding small in all except engine wheels. This remark applies especially to those carriage and wagon wheels in which the spokes and rim are of flat bar iron bent into segmental forms, the section of the rim not being one-half that assumed. It is not, therefore, necessary to enter into further calculations on this point, as the resistance offered by such wheels to the contraction of the tire must be insignificant in comparison with the tensile strength of the latter.

No account has, however, been taken of the plasticity of the material of the tire, which, especially at high temperatures, allows of its elongation by the force of its own contraction, the residual strain being only equal to the difference between the total force of contraction and that already expended at the higher temperatures in the elongation of the tire; so that even were there a much greater original difference between the diameters of the tire and rim than has been assumed, the resulting strain would probably be little more, as plasticity increases, and the mechanical equivalent of expansion by heat decreases, rapidly, with the rise to such high temperatures as would be necessary to enlarge the diameter sufficiently to get the tire on the wheel.<sup>1</sup>

It would seem, therefore, that the shrinking on of these tires cannot alone result in the production of a strain sufficient to cause their fracture, unless they are of bad material or workmanship. If, however, a strain approaching the tensile resistance to fracture of the material of the tire could be thrown upon it, by the elongation demanded by the difference between the diameters of the wheel and of the tire, the latter should break upon first being put to work, instead of after long wear, as is usually the case. For if that strain were alone the cause of fracture, its intensity would be constantly reduced by the tendency working would have, to make the tire accommodate itself by further elongation. Fracture frequently takes place at several points simultaneously, but it seems difficult to conceive that a simple tensile strain should induce such a phenomenon, as a tire would be relieved of all tension by one fracture, every additional fracture demanding an equal

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<sup>1</sup> *Vide* Mallet "On the Physical Conditions involved in the Construction of Artillery," &c., pp. 40 and 152.

strain for its production. Assuming, however, that the material of the tire is perfectly homogeneous, and of uniform tensile strength, and that the circumferential strain is equally distributed throughout the entire length of the tire, then it is possible to conceive, that a strain equal to the tensile strength of the tire could fracture it in several places simultaneously. But unless the above conditions rigidly obtain, absolute simultaneity of multiple fracture would be impossible, and it need hardly be said that practically such conditions never exist. Except multiple fracture take place with absolute simultaneity, it could not occur as a result of tensile strain, for the first fracture would render subsequent fracturing impossible, because it would have dissipated the strain that produced it; so that any further breakage would necessitate the reproduction of a tensile strain slightly in excess of that which produced the first fracture, and for which there is no origin.

By far the larger number of broken tires have been fractured in several places, and of the 80 cases reported upon by the officers of the Board of Trade up to the end of 1874,

9	were fractured at	3 places,
8	"	" 4 "
5	"	" 5 "
5	"	" 6 "
2	"	" 7 " and
6	"	" in "several places;"

while out of 14 cases reported by the Great Western Railway Company between 1868 and 1873,

3	were fractured at	3 places,
2	"	" 4 "
2	"	" 5 "
1	"	" 7 "
1	"	" 12 or 14 places,
1	"	" several places.

Many of those reported in 1875 also broke in several places. This large number of multiple fractures affords strong evidence of the existence of enormous internal molecular strains in the material of the tire, for it seems impossible to conclude, that a tensile strain, or inferiority of material or workmanship, even when aided by impact strain, should be disclosed by such results.

Fracture has as frequently been assigned to the reduction of the sectional area of the tire, by the holes made to receive the rivets,

bolts, or screws, by which the tire is fastened to the rim of the wheel. Any such reduction of sectional area undoubtedly lessens the tensile strength of a tire. But unless these holes diminish that strength, by a proportion far greater than that borne by the reduced to the full section, it seems impossible to attribute fracture to this cause alone. In many of the forms of fastening by screws, this reduction in section is very small, for the screw-hole only enters the tire a short distance, and that, in some instances, just under the flange, where the tire is strongest. Even allowing, however, that such holes sufficiently lessened the strength of the tire to cause fracture at these points, it would not explain fracture at several points, nor fracture between two such planes of weakness. Many tires have broken in places where no such planes of weakness existed, the tire being fixed by clips, or by annular clip rings. Again, referring to the reports already quoted, it will be found that out of the 80 accidents in 1874, twenty-three tires were fractured through the solid material, and not through either a weld, or a bolt or screw-hole, although all these existed. Seventeen tires were weldless, and seven were fixed by clips or clip rings, without bolt or screw. Of these, one was fractured in five and one in six places; while the fourteen fractured tires reported by the Great Western Company between May 1868 and May 1873 were all affixed by Gibson's fastening. Of the tires that failed in 1875, four hundred and seventy-seven were fastened by bolts or rivets, but of this number only  $19\frac{1}{2}$  per cent. broke at the bolt or rivet-holes. These facts prove that the force which initiated fracture was not one of simple tension aided by impact, and that fracture was not due to reduction of sectional area of the tires by the bolt-holes. Further explanation of the nature of the forces productive of the fracture of a tire of good material must therefore be sought.

The alleged reduction of the strength of iron by, as well as the contraction due to, low temperature, has usually been called in to explain the fracture of tires during a frost. The effect of extreme cold upon the tensile strength of iron has not yet been definitely ascertained, though the experiments of Fairbairn<sup>1</sup> tend to the conclusion that the tensile strength of iron, not already 'cold short,' in ordinary frosts in this country, is not materially reduced, a conclusion supported by experience in Russia and Canada, where the

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<sup>1</sup> *Vide* Report of the Seventh Meeting of the British Association for the Advancement of Science, vol. vi., p. 377; and "On the Application of Cast and Wrought Iron to Building Purposes," p. 63.

cold is far greater and more protracted than in England. The moderate speed of trains observed abroad, compared with that adopted in England, undoubtedly tends to reduce the number of breakages, and the severity of the accidents attending them; but against this may be set, the superiority of English permanent way, and its better maintenance. If the difference in the strength of iron in summer and in winter were considerable, and sufficient in itself to cause fracture of a railway tire, it would be unsafe to travel in any common carriage over many of the ill-laid granite pavements during severe frost, except at low speed. None of the axles would withstand the severity of the shocks delivered through the wheels, at a velocity due to the recoil of a loaded spring, as they pass rapidly from summit to hollow of every inequality of the roadway. Again, so general a cause as frost should be evidenced by corresponding effect, and if productive of fracture of railway tires, it should be manifest by more frequent fracture, and not by isolated instances. Although there seems to be little proof, that the strength of iron to resist static strains is reduced by a low temperature, there is evidence that its power of resistance to impact is somewhat diminished by such a condition, although probably only by a fraction of the extent often assigned to it. If this reduction in strength were sufficient to cause the fracture of one tire in a train, all the rest of the tires of the same train, running under the same conditions of temperature, should be fractured, unless that one tire was of originally bad material, or was weakened by a defective weld or by a bolt-hole. But such has not always been the case, many tires having broken through solid and good material, and not at a weld or bolt-hole, although both have existed in the tire. Again, if low temperature alone could initiate fracture, the lowest temperatures should be most fruitful of such results; so that the intense cold of some countries would be accompanied by such numerous tire and axle breakages, as to make railway travelling almost impossible, except at very low speeds.

Although there is no evidence to show that the occurrence of a moderate frost can by itself reduce the resistance of iron to impact strains, so as to make a tire unable to withstand the shocks brought to bear upon it, there is sufficient proof that frost, in conjunction with other causes, exerts some influence in bringing about a fracture which without it would have been delayed.

Of the 94 accidents before referred to, 17 per cent. happened in the spring, 14 per cent. in the summer, 9 per cent. in the autumn, and 59 per cent. in the winter; thus the number of fractures

[1876-77. N.S.]

during the three hottest months has been only 23 per cent. of the number in the three coldest months. But these figures do not correctly represent the comparative strength of iron under different temperatures; for the hardness of the ground during frost, by diminishing the resilience of the way, and thus converting it into an anvil, may well account for the excess of fractures in the winter, resulting from the severity of the impact strains which the tires have at such times to bear. As a result, however, of the much wider range of observation and systematic record in 1875, the relation given by the above figures is reversed; for in that year fifty tires failed in January, thirty-one in February, thirty-eight in March, seventy in April, seventy in May, sixty-seven in June, sixty in July, fifty-nine in August, fifty-seven in September, fifty-seven in October, sixty-four in November, and sixty-one in December; the greatest numbers being in April and May, and the smallest in January and February.

Of 61 steel tires which broke on the Moscow-Nishni railway during the winter of 1871-2, the cause of fracture could only be ascertained in 18 cases, the fractured surfaces being rusted; but 8 of these were attributed to inferior metal, 7 to excessive strain in putting on the tires, and 3 to indifferent quality of metal combined with too great wear. Fourteen tires broke through bolt-holes, and three through screw-holes, while no breakages occurred with the tires on Mansell's wood wheels.<sup>1</sup> Thus the actual cause of fracture can only be considered as ascertained with certainty in about 17 of these cases, the remainder, including most of those in the 18 enumerated, being of unexplained origin. As no breakages occurred with Mansell's wood wheels, and steel tires were more affected by frost than those of iron, it seems obvious that the excess of fractures during winter is mainly due to severe impact caused by the hardness of the way.

The number of axles broken on the German railways during 1873 was 77 in the six warmer months against 68 in the six colder months; and though the winter was a mild one, the fact affords a striking proof of the uncertainty of the alleged decrease of the strength of iron during frost. Were very low temperature by itself so active a cause of the fracture of railway tires, it might have been expected that every frost would have been marked by fractures; but long periods have elapsed with comparative immunity from such accidents, followed by a shorter period marked by their excessive frequency. Thus it was found that the

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<sup>1</sup> *Vide* Minutes of Proceedings Inst. C.E., vol. xxxix., p. 351.



accidents from broken tires reported upon on the Midland railway between 1847 and 1871, a period of twenty-three years, only numbered 5, while between January 1871 and December 1874, or in four years, no less than 10 such accidents occurred on the same railway, that is, double the number in about one-sixth of the time. This proves that the cause must be of slow growth, and that the breaking strain must be so nearly approached, that an unusually severe shock or a slight reduction in strength, such as might be caused by frost, is all that is necessary to complete the conditions of fracture.

The contraction of a tire during frost has been sometimes supposed to cause its fracture, by throwing an increased tensile strain upon it; but this supposition seems without foundation, for the wheel body is subject to the same conditions of temperature, and the co-efficient of contraction of the materials of the tire and wheel cannot be materially different. Let it be assumed, however, for the sake of argument, that a wheel body, of perfectly rigid material, not subject to alteration in volume by alteration of temperature, is surrounded by a wrought-iron tire, 150 inches long and 10 square inches in section. Suppose now that the tire cools through a range of 20° Fahr., or from say 50° to 30° Fahr., and that its co-efficient of lineal contraction = 0.0000064. Its lineal decrease will then be 0.0192 inch, and the mechanical equivalent of this reduction will be 1.5 ton per square inch, or 15 tons on the whole tire, a strain quite insignificant compared with its ultimate strength, even upon the assumption of the above physically impossible conditions.

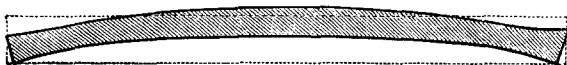
The foregoing theories have been most frequently appealed to when the cause of fracture has not been self-apparent; but the Author believes them to be inadequate to explain, first, the fracture of tires of good material and workmanship; secondly, the fracture of tires at several places; thirdly, that a railway may be free from such breakages for a long period, followed by a shorter period of frequent breakage; fourthly, the fracture of tires at several places through the solid part rather than through bolt or rivet-holes; fifthly, that tires generally have run several thousand miles before they fly to pieces.

The strain caused by shrinking on an engine tire, and that of centrifugal force at high speeds, when combined with the loss of strength and the severity of impact during frost, may together amount to a considerable portion of the total resistance of its material. As they cannot, however, be considered sufficient to explain fracture in many cases, the Author will proceed to describe

what seems to be the cause of those strains which must exist in a tire at the moment of its fracture; and for this purpose will refer to some well-known facts which, so far as he is aware, have never yet been appealed to.

If a flat stout bar or piece of plate of cast or wrought iron, or other metal, be subjected on one of its surfaces to long-continued light hammering or rolling when cold, that surface will become compressed or elongated to an extent dependent upon the duration and intensity of the hammering or rolling. If the plate or bar be thin the effect of compression by hammering will extend throughout its thickness, and little change will result except of tension in orthogonal directions in the plane of the surface; but if the plate or bar be thick, relatively to one or both of its other dimensions and to the force producing compression at any moment upon one surface only, the effect will be that that surface will be compressed and elongated in all directions, while the opposite surface will remain unchanged. The effect of thus altering the relative dimensions of the two surfaces, of the originally flat plate or bar, will be to make it assume the form of an umbo, or of a bow with the convexity towards the rolled or hammered surface. The amount of this convexity depends upon conditions attending the rolling or hammering, as well as upon the duration and intensity of these. Examples of this elongation of one surface of a plate or bar, and its attendant results of convexity of that surface, are not infrequent. A familiar example of its practical application in the foundry, is that of straightening cast-iron plates, such as coping plates which have become bent in cooling, by placing the convex side upon an anvil, and lightly hammering the concave side. Tramway plates, under the rolling action of the wheels of heavily-laden vehicles, afford another example. These, if of sufficient thickness to give the desired protection to a roadway,

FIG. 1.



Section of a tram-plate from Westminster Bridge taken up in 1873. The dotted lines represent the original form and thickness of the plate as put down in 1861.

become converted into shallow inverted dishes. Fig. 1 is a section of a tram-plate put down on Westminster Bridge in 1861, and taken up in 1873, after twelve years' wear. It affords an example of the intensity of the differential strains thrown upon the material of the plate by which the curvature has been effected, because a

large portion of the surface has been worn away, chiefly by the aid of the sand and dirt with which the plates are always covered. This grinding away of the surface of the plate contemporaneously with its compression almost wholly prevents the accumulation of the bending force, for the compressed material which would exert that force is nearly all removed; so that the fact of the production of the curvature of these plates, under such conditions, is a strong proof of the forces brought into play by the rolling action of the wheels of loaded vehicles. Although it took twelve years to produce the curvature shown by the section, a less number of years would, under more favourable conditions, suffice to bring about the same result.

At the time of the Crimean war, a portion of Woolwich Arsenal, traversed by heavily-laden vehicles, was covered with cast-iron plates, for the purpose of protecting the roadways and reducing the draught resistance upon them. After these plates had been down a few months, they assumed the form of inverted shallow dishes, and it was in consequence necessary to take them up. In each of these examples the plate was vertically free, and the force exerted by the extended upper surface was expended in the production of the curvature described. But if the bending thus originated had been opposed by a competent resistance, the internal molecular strains engendered by the extension of one surface would gradually have become sufficient to cause rupture, either by the crushing of the upper portion of the plate, or by the tearing asunder of the lower portion, just as an arched rib, loaded with a breaking weight, and supported only at its lower extremities, would give way by crushing or crumpling at the upper, or by tearing asunder at the lower edges or flanges. Many more illustrations might be adduced, but it is unnecessary to dwell upon them. It now remains to correlate these facts, and to draw such conclusions as they warrant, in explanation of the conditions involved in the often apparently anomalous fracture of railway tires.

From what has been said, it will not be difficult to see that the rolling and hammering action, to which railway tires are subjected, must so extend and compress some parts of their outer surface, as to create those internal molecular strains, the result of which is illustrated in a small degree by Fig. 1. From the time a tire is put to work, and begins to roll under its load along the hard road of iron or steel, it is subjected to a "rolling out" of the surface, at a rate depending principally upon the load, the velocity at which it is impelled, the elasticity of the wheel and the permanent

way, and the nature of the material of which the tire and the rails are composed. If the pressure upon a unit of surface of the tire were only such as to bring into play the elasticity of the material, no extension or permanent compression would take place; but as the pressure upon the small surface, at any moment in contact with the rail, is vastly greater than that necessary to surpass the elastic resistance of the material, it loses ductility, and permanent compression and elongation of the surface are the result.

Every revolution of the wheel is attended by a fresh permanent loss of ductility of the material of the tire; for although repeated application of a similar weight or pressure may not reduce its elastic resistance, the ductility will be drawn upon by every fresh application of the pressure, until all ductile resistance is lost, and rupture approached. Thus film after film of the tread of the tire is permanently compressed and elongated, until the thickness so molecularly altered becomes sufficient to create internal differential strains upon the tire, of such magnitude as to surpass its resistance to rupture, or so nearly to approach it, that an unusually heavy impulse, or other extraneous force, is alone necessary to effect such a result. Considering the small surface of tire at any moment in contact with the rail, and that the load upon this small surface per unit is very great; that the velocity with which the wheel is impelled is often 90 feet per second; and that the speed with which a tire strikes any projection, or descends from one level to another, as at a defective fish-joint, is that due to the recoil of a heavily loaded spring, probably approaching 1,000 feet per second,—it is not difficult to see that the compression of the tread of a tire under such conditions may be very rapid, and a run of a few thousand miles sufficient to create strains productive of fracture. Thus, when the outer and lengthened portion of a wheel tire is under compression, and the inner portion correspondingly under tension, at some period this compression and tension will end in a tendency to tear asunder the inner portion, or to crush or crumple up the outer portion. Or,—as would seem to be more generally the case,—these antagonistic forces, in equilibrium while the wheel is running smoothly, will insure the ruin of the tire as soon as that equilibrium is destroyed, by a blow such as is sure to be met with while running at high speeds with heavy loads.

Confining attention for the moment to a tire without weld, and without screw or bolt-holes, it may be assumed that the differential forces are diffused equally throughout the whole length. When,

therefore, these forces are nearly equal to the total resistance of the tire to rupture, being elastic forces, they will, on an abnormal shock being delivered upon the tire, cause it to burst, because the forces tending to rupture at every point in its length are thus made to exceed those resisting them, in a time measured by the transit velocity of wave-impulse through a homogeneous material. This is probably not less than 1,500 feet per second, so that the shock may be considered as practically simultaneous throughout the length of the tire. The forces, therefore, which previous to the shock were supposed to be equilibrated by their resistances, being internal, tend, when that equilibrium is destroyed, to produce fracture at every point in the tire. A flat tram-plate which has its upper surface compressed and elongated, being vertically free, can accommodate itself by an upward convexity to the condition of differential surface dimensions; but the circular form of a railway tire prevents any such accommodation by bending. Instead, therefore, of the differential strains being expended in producing change of form, the tire is, in any assumed segment, in a condition analogous to that of a bent girder loaded on the convex side by a force which, when aided by a slight shock or other extraneous addition, becomes sufficient to overcome its resistance to rupture.<sup>1</sup> It will, however, be seen that it is not a necessary condition that every one of several fractures in a tire should take place with absolute simultaneity, because the precedence of one fracture will render those internal forces which produced it free to initiate fracture in as many places as may be necessary to satisfy or expend the internal differential strains. These strains may, when one fracture has taken place, be dissipated by the bending of the tire.

But besides explaining the conditions of fracture of a tire not weakened either by a weld or by bolt or screw-holes, it is necessary to consider the fracture of tires weakened by these—not indeed to find the explanation of fracture at such points of weakness, for that may perhaps be considered as sufficiently obvious, but to find the reason of fracture when that takes place through the solid material of the tire, and not through screw or rivet-holes.

In the accident at Shipton, in December 1874, the tire was affixed to the body of the wheel by four rivets. The tire broke at two places, each about midway between two rivet-holes, through the solid

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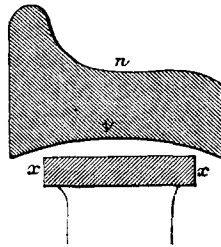
<sup>1</sup> This illustration is not, however, strictly accurate, as the strains in the girder will be greatest at the centre; but with the tire the strains will be uniform throughout any assumed segment.

material, which was iron, though one fracture was surmised to be at a weld. This is only one of many cases of fracture through the full section rather than through the reduced section at a rivet or bolt-hole. The explanation is not difficult. At a rivet or bolt-hole, the continuity of the tire is broken; and as these holes are usually near the centre of the tread of the tire, the continuity is broken just at the part subject to the greatest compression. The result of this is that round these holes the tangential and transverse compression, produced by the impeded elongation of the material, is dissipated in an upward flow of the particles, tending to the production of a crater-like ridge, somewhat less in internal diameter than the bolt or rivet-head. This ridge is never actually produced, but is worn off either by the ordinary running, or by the break-blocks, as fast as it tends to rise above the normal surface of the tire, which at these points is relieved of almost all strain. Hence a tire, considered in reference to the forces suggested as productive of fracture, may, after it has been some time in work, be stronger at a rivet or bolt-hole, particularly as against impulse, than at a point in the solid material at some distance from it. The above may be thus illustrated:—If one end of a piece of iron of small section be subjected to repeated blows from a hammer, the result is, as in making a rivet-head, the hammered particles flow outward in all directions from the centre. But if, instead of the piece of small section, the same amount of hammering be done upon the centre of one surface of a piece of thick flat plate, the work will be consumed in compressing or elongating a portion of that surface, tending to make the plate assume an arched form, because the hammered particles, which were free to move in forming a rivet-head, are confined by the surrounding and underlying unhammered particles in the plate.

The differential strains created in a tire are less simple than have been hitherto considered, for the compression and elongation is most intense toward the centre of the surface, so that the tire is subjected to a transverse strain as well as being, like the centre portions, under compression. In a flanged tire, these strains are more complex, as the flange is not compressed, but, like the interior portions of the tire, remains unaltered except by the tensile strain thrown upon it by the compressed portions of the tread. Thus the tire may be considered as consisting of three portions, rigidly connected, the central portion, under a great compressive strain, being resisted by and tending to lengthen the two others, until the tensile strain, aided by an impact force, becomes sufficient to overcome their resistance to rupture. The conditions indeed

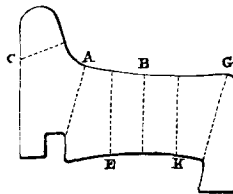
warrant the suggestion, that the fracture of a tire is of a character such as is induced by a bursting strain. As a proof of the existence of the strains here appealed to, it may be mentioned that many tires when taken off the wheels present internal transverse curvature, as shown in Fig. 2, though when the tire was new

FIG. 2.



this surface was flat. This curvature has the effect of keeping many tires tight on the wheels that would otherwise become loose. Although the rolling of the tire increases its diameter at  $v$ , the curvature tends to diminish the diameter at  $x, x$ . Of the 684 failures in 1875, three hundred and fifty-nine tires are reported as having split "longitudinally." Of these twenty-three broke at A (Fig. 3), fifty-eight at B, fourteen at C, seventeen at E,

FIG. 3.



twenty-one at G, and six at K. It will be seen that the number split at B was more than double that elsewhere, the tendency to rupture from the compression of the tread, and the condition of support being greater at that point than at any other, the static and impact strains being chiefly developed at  $n$ , Fig. 2, and the support being at  $x, x$ .

It must be pointed out that the conditions brought forward, as to the origin of fracture of a large number of railway tires, do not obtain with the tires of the wheels of ordinary vehicles. In their case, the surface in contact with a macadamised road is always much greater than with a railway tire upon a rail, and the pressure per

unit of surface is therefore much less, whilst their running velocity rarely exceeds one-sixth that of a railway wheel, so that the conditions necessary for "rolling out" the surface are absent.

It would seem then that the tires upon elastic wheels have some advantage over those on non-elastic wheels, as the compression of their surface must proceed more slowly than with those upon wheels almost rigid, which act as anvils for the tires to be rolled out upon. Still it is only a matter of greater length of time for them to fail by reason of the internal differential strains.

Having now described what the Author believes to be the principal cause of the fracture of railway tires, it remains to make a few collateral remarks on the subject. If his theory be correct, however good the material and workmanship of a railway tire, it must gradually become unsafe from other reasons than simple loss of thickness; for, whether it be of steel or of iron, it is amenable to the production of internal molecular strains consequent upon the rolling out and compression of its outer portions, which must at some time become of sufficient magnitude to initiate fracture.

If steel tires or their outer portions could be hardened without sacrificing any of their resistance to rupture by impulse, their durability would unquestionably be greatly increased. The tire would then partake of the character of a hammer with a hardened steel face; the rails upon which it ran would undoubtedly suffer more from deformation of their surface than by unhardened steel or iron tires, but the life of a tire and its resistance to surface compression would, like the hardened hammer face, be increased. The durability of the American chilled cast-iron car-wheels is probably owing to the extreme hardness of their running surface, and their consequent resistance to surface compression. Unchilled cast-iron railway wheels would probably be fractured after running a few hundred miles by the forces described. These views afford an explanation of the cause of the breaking off of small patches from the tread of chilled cast-iron wheels; the detachment of which dissipates the strains induced by compression.

Although the duration of the tire in an elastic wheel is increased, yet as the tire has still to carry a load, its surface must be subject to deformation. That deformation will not proceed quite so rapidly as with a nearly rigid wheel, the inertia of which upon impact strain would have to be overcome by the tire before it was relieved by the springs of the vehicle under which it was running; whereas a good elastic wheel may be considered as having somewhat the character of a spring, and, in so far, being



without such inertia. The tires of wheels fitted with breaks probably have their liability to fracture slightly diminished, especially where cast-iron break-blocks are used, as some of the compressed portions are more quickly worn off by these, and by the skidding upon the rails, than with tires not so circumstanced. From this it might be expected that the vehicles of metropolitan railways, on which stoppage at every few hundred yards necessitates the frequent application of breaks, should be peculiarly free from fractured tires; for a large number of the wheels of every train carry breaks and frequently run skidded for considerable distances upon the rails, so that the wear must be great, and is probably sufficient to dissipate the strains that would accumulate if the tires were not so worn.

The lamination of the surface of rails, particularly noticeable where the traffic is great, is an illustration of some of the effects of the rolling-out action of the wheels. The head of the rail not being wide, and the rolling being as much on one side at least, as at the centre, the portions rolled and compressed are comparatively free to flow towards the sides of the rail, where they become detached, and with rails of inferior quality lamination takes place. Tires of similar material would probably be somewhat relieved by lamination from the strains induced by rolling; but what would be gained in this respect would be more than counteracted by the loss of strength of the material.

With reference to the fastenings for railway tires it would seem, that the ultimate strength of a tire, as against ordinary wear and tear, is not reduced by the method of fastening on to the wheel by rivets or bolts. Of the 550 reported fractures in tires fastened by this means 79 per cent., or nearly four-fifths, were fractured through the full section; some of which were affixed by screws from the inside of the tire, and only penetrated partly through it. Had these been fastened by rivets or bolts passing quite through them, it is probable that the number of fractures through the solid metal would have been proportionately greater than 79 per cent. Notwithstanding this, however, the best mode of fastening is unquestionably by annular clip rings and grooves on both sides of the tire, so as to prevent the portions of a fractured tire from leaving the wheel, as it is from the latter cause that the lamentable results of some of these fractures are to be ascribed.

With a view to the prevention of the fractures of tires, the Author ventures to suggest that:—

1st. No tires should be allowed to run more than a certain number of miles, dependent upon the character of the vehicles they

are running under, upon the section and material of the tires themselves, and upon the hardness of the rails. At present no sufficient information exists upon which to base an arbitrary mileage, as till recently no systematic accounts of the number of miles run by tires were kept, so that the safe mileage of various kinds of tires under the different kinds of vehicles and engines remains to be determined, by careful experiment and extended observation.

2nd. That the condition as to wear of the surface of tires should be watched with the greatest care, and when the yet to be prescribed mileage has been run, the tires should be re-turned, or, if that be not requisite, then they should be heated to a sufficiently high temperature to allow of the dissipation of the internal molecular strains, and of a rearrangement and repose of the disturbed particles. The tires might then, if not worn out, be replaced.

In conclusion, it is not pretended that the statistics in this Paper are complete, as until 1873 the railway companies did not report the accidents on their lines. The figures quoted are of those accidents reported upon by the Board of Trade officials between 1847 and 1873, with the exception of the 14 by the Great Western Railway Company between 1873 and 1874, and those reported by all the companies in 1875, many of which resulted in no accident. They do not represent all the fractures, nor the number of miles in every case run before each tire was fractured; but they do give, in a large proportion of 550 cases, the particulars and date of fracture, and the mode of fastening, and they are sufficiently illustrative for the immediate object of this Paper.

Although the Author has not been able to bring forward the results of exhaustive experiments and observations in support of the propositions he has made, it is hoped that the arguments he has adduced will lead those who have the means to consider it worth the time and trouble to carry out such experiments and observations.

The Paper is illustrated by several diagrams, from which the woodcuts, Figs. 1 to 3, have been prepared.

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[Dr. PERCY