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“Recent Researches in Friction.”¹

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IN recent scientific researches, the investigation and study of the laws of friction must certainly be classed amongst the most important. Until lately, erroneous and vague views were entertained, mainly on account of the absence of any well-ascertained data based on scientific and practical experiments, although the great importance of the subject was fully realized. This department of applied science claims the careful attention and study of the practical engineer as well as of the theorist, from the fact alone that frictional resistance is a constant and ever-recurring source of waste work; but in order that the student may arrive at a correct conclusion, he must examine the most recent experimental results, for the whole subject has been completely revolutionized within the last few years.

Amongst the first explorers in this field of labour was one of the most original and scientific engineers of the last generation, namely, the late General Morin, who gave much time to this subject, and obtained results of a very varied nature both with dry and with lubricated surfaces on every possible constructive material. Owing, however, to the extremely low pressure and speeds with which he worked, his results are not regarded as of much value in the light of modern experiments, such as those of Professor Thurston, Mr. Beauchamp Tower, M. Inst. C.E., under the auspices of the Institution of Mechanical Engineers, and of Mr. W. Stroudley, M. Inst. C.E., who experimented in a more practical manner on the axles of railway trains and locomotives, under conditions similar to those encountered in actual practice. Engineers in America have been working in a similar direction; Mr. Woodbury on the friction of revolving disks; Mr. Wellington on the total resistance of trains, which includes the friction on the journals, tires, &c.; and last, but by no means least, there

¹ This Paper was read at a meeting of the Students on the 20th of November, 1885.

are the well-known experiments of Messrs. Galton and Westinghouse, on the brake-friction of railway vehicles, the most important of which were carried out on the Brighton Railway with the co-operation of Mr. Stroudley.

The Author's object in contributing this Paper is to compare these various results, and to examine the phenomena which have been obtained from a theoretical point of view. The laws of dry friction must be considered from an entirely different standpoint from those of the friction of well-lubricated surfaces, although in some cases it is a very difficult, if not an impossible

FIGS. 1.

task to define accurately where the one condition begins and the other ends; for example, some revolving journals, although originally fully lubricated, behave as dry surfaces when the supply of lubricant diminishes. The apparatus used by the most recent experimenters is shown in the illustrations. Figs. 1 represent Professor Thurston's machine. F, the journal on which it is desired to measure the frictional-resistance, is driven by a belt running on the pulley E. The brass, G, is fitted into the upper part of the pendulum HH; the desired pressure on the brasses is applied by turning the hand-screw K, which compresses the spiral spring S; PP is a graduated arc transversed by the pointer O, which is attached to the pendulum. The quotient of this reading by the total pressure indicated by the pointer X gives the co-

efficient of friction. On the top of the brass is a thermometer to register the heat of the journal; R is a revolution-indicator; the lubricant is supplied through a small hole at T. When the journal revolves the friction on the brass causes the pendulum to be deflected.

Mr. Tower's machine, Fig. 2, resembles the last in some points, but for the spiral spring a dead weight is substituted to give the desired load on the brass. A is the revolving journal, B is the brass bearing, carrying the frame C, on the lower part of which is a knife-edge C', situated immediately under the centre of the journal, from which is suspended the weights; D is a long light

FIG. 2.

angle-iron frame with a scale-pan suspended from its extremity, into which are placed weights to counterbalance the turning moment of the friction. E is a pointer and graduated scale to indicate when the whole frame is in its normal position. H is an oil-bath into which the bottom of the journal dips, and so keeps up a thoroughly good supply of lubricant.

In Mr. Stroudley's machine, Figs. 3, the essential difference from the last-mentioned is the arrangement for applying the load to the brass. A is the revolving journal, several sizes of which are used corresponding to the various axles of a train. B is the brass bearing fitted into the weight-beam C, at each end of which is a knife-edge carrying a weight-suspending link D. G is a small scale-beam and pan into which weights are placed to counterbalance the moment of the friction. H is a small eccentric

and wheel, driven by a worm on the main shaft, which keeps the bearing continually moving to and fro to represent the side-play always given on locomotive axles. M is an oil-pad which keeps the journal constantly lubricated. N is a siphon lubricator. R is

FIGS. 3.

a revolution indicator. T is a thermometer to register the heat of the journal. P indicates when the beam is in its normal position.

The frictional resistance is calculated thus (Fig. 4):—

Let x = radius of the journal in inches.

W = the total load on the brass in ozs.

Then with the dimensions as shown, a weight in the scale-pan acts at a leverage of $72 \div x$ on the surface of the journal; so that 1 lb. in the pan is equivalent to $\frac{72}{x}$ lbs. frictional resistance on the brass. Then—

$\frac{72}{Wx}$ = the coefficient of friction corresponding to each oz. in the scale-pan.

The total frictional resistance on the brass =

$$\frac{72 \text{ (weight in scale-pan)}}{x}$$

The frictional resistance per square inch =

$$\frac{\text{Total frictional resistance}}{\text{nominal area of brass}}.$$

FIG. 4.

The nominal area = the length of the journal $\times$ the chord of the arc of the brass in contact. The HP. required to overcome this resistance is calculated by formulas given further on. By comparing and examining the observed results obtained from these machines, the following laws become apparent.

WELL-LUBRICATED SURFACES. (Oil-bath.)

1. The coefficient of friction with the surfaces efficiently lubricated is from $\frac{1}{6}$ to $\frac{1}{10}$ that for dry or scantily lubricated surfaces.

2. The coefficient of friction for moderate pressures and speeds varies approximately inversely as the normal pressure; the frictional resistance varies as the area in contact, the normal pressure remaining constant.

3. At very low journal-speeds, the coefficient of friction is abnormally high; but as the speed of sliding increases from about 10 to 100 feet per minute, the friction diminishes, and again rises when that speed is exceeded, varying approximately as the square root of the speed.

4. The coefficient of friction varies approximately inversely as the temperature, within certain limits, namely, just before abrasion takes place.

The evidence upon which these laws are based is taken from various modern experiments. That relating to Law 1 is derived from the "First Report on Friction Experiments," by Mr. Beauchamp Tower.

TABLE X.¹

Method of Lubrication.	Coefficient of Friction.	Comparative Friction.
Oil bath	0·00139	1·00
Siphon lubricator	0·0098	7·06
Pad under journal	0·0090	6·48

With a load of 293 lbs. per square inch, and a journal speed of 314 feet per minute, Mr. Tower found the coefficient of friction to be 0·0016 with an oil bath, 0·0097 with a pad, which is six times the amount of friction with the latter. Under the same conditions, Mr. Stroudley obtained a coefficient of 0·00961, which is a very close approximation.

The very low coefficients obtained by Mr. Tower will be accounted for by Law 2, as he found that the frictional resistance per square inch under varying loads is nearly constant.

TABLE I.²

Load in lbs. per square inch	520	468	415	363	310	258	205	153	100
Frictional resistance per square inch	0·416	0·514	0·498	0·472	0·464	0·438	0·43	0·458	0·45

It should be noted here that the frictional resistance per square inch is the product of the coefficient of friction into the load per square inch on horizontal sections of the brass. Hence, if this product be a constant, the one factor must vary inversely as the other, or a high load will give a low coefficient, and *vice versa*.

¹ Institution of Mechanical Engineers. Proceedings, 1883, p. 651.

² *Ibid.*, p. 643.

For ordinary lubrication, the coefficient is more constant under varying loads; the frictional resistance then varies directly as the load, as shown by Mr. Tower in Table VIII. of his report,¹ and also

FIG. 5.

from the following results obtained by Mr. Stroudley with a pad of standard Globe oil, as used for carriage-axles on the Brighton Railway.

Load per square inch on Brass.	Coefficient of Friction.	Frictional Resistance per square inch.
Lbs.		Lbs.
333	0.00792	2.639
293	0.00800	2.34
251	0.00770	1.93
237	0.00720	1.70

With respect to Law 3, Mr. A. M. Wellington, of the American Society of Civil Engineers, made a large number of experiments, on journals revolving at very low velocities, and found that the friction was then very great, and nearly constant under varying conditions of the lubrication, load, and temperature. But as the

¹ Institution of Mechanical Engineers. Proceedings, 1883, p. 650.

speed increased the friction fell slowly and regularly, and again returned to the original amount when the velocity was reduced to the same rate.¹

The following Table shows this clearly (Fig. 6):—

Feet per minute	0 +	2·16	3·33	4·86	8·82
Coefficient of friction	0·118	0·094	0·0705	0·0685	0·055
Feet per minute	21·42	35·37	53·01	89·28	106·02
Coefficient of friction	0·047	0·040	0·035	0·030	0·0255

FIG. 6.

It was also found by Professor Kimball, that when the journal velocity was increased from 6 to 110 feet per minute, the friction was reduced 70 per cent.; in another case, the friction was reduced 67 per cent. when the velocity was increased from 1 to 100 feet per minute; but after that point has been reached the coefficient of friction varies approximately with the square root of the velocity, this law was pointed out by the late Mr. W. R. Browne, M. Inst. C.E.² The observations are by Mr. Tower.

¹ Transactions of the American Society of Civil Engineers, 1884, vol. xiii., p. 409 *et seq.*

² The Engineer, 1884, vol. lviii., pp. 57, 58.

COEFFICIENTS OF FRICTION, FOR SPEEDS AS BELOW (FIG. 7).

Feet per minute.	209.	262.	314.	366.	419.	471.	Nominal Load per square inch.
Observed . .	0·0010	0·0012	0·0013	0·0014	0·0015	0·0017	Lbs.
Calculated . .	0·0010	0·00118	0·00123	0·00132	0·00141	0·0015	520
Observed . .	0·0013	0·0014	0·0015	0·0017	0·0018	0·002	468
Calculated . .	0·0013	0·00145	0·00159	0·00172	0·00184	0·00195	
Observed . .	0·0014	0·0015	0·0017	0·0019	0·0021	0·0024	415
Calculated . .	0·0014	0·00157	0·00172	0·00185	0·00198	0·0021	

FIG. 7.

The variation of friction with temperature is approximately in the inverse ratio, Law 4. Take, for example, Mr. Tower's results, at 262 feet per minute, as shown in the following Table:—

Temperature, Centi- grade	43·4	37·8	32·2	26·7	21·1	15·6
Observed	0·0044	0·0051	0·006	0·0073	0·0092	0·0119
Calculated	0·00451	0·00518	0·00608	0·00733	0·00964	0·01252

This law does not hold good for pad or siphon lubrication, as then the coefficient of friction diminishes more rapidly for given increments of temperature but on a gradually decreasing scale until the normal temperature has been reached ; this normal temperature increases directly as the load per square inch, as shown in the

FIG. 8.

following Table taken from Mr. Stroudley's experiments with a pad of rape oil (Fig. 8) :—

Temperature, } Fahrenheit	105	110	115	120	125	130	135	140	145
Temperature, } Centigrade	40.56	43.34	46.1	48.9	51.7	54.4	57.2	60	62.78
Coefficient .	0.022	0.0180	0.0160	0.0140	0.0125	0.0115	0.0110	0.0106	0.0102
Decrease of } coefficient . }	..	0.0040	0.0020	0.0020	0.0015	0.0010	0.0005	0.0004	0.0002

From the above considerations it may be fairly assumed that
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the friction of lubricated surfaces is very different in nature from the friction of dry surfaces. One essential point is that in well-lubricated surfaces the brass and journal are not in contact, but are separated by films of oil, the one adhering to the brass, the other to the journal. The resistance, therefore, is due to the shearing action between the two films. There is no doubt whatever but what this film actually exists, for the brass with its load is bodily raised as soon as the journal begins to revolve. The Author has not only proved this for himself, but has also measured accurately the thickness of the film with a piece of apparatus of his own design. The experiment was carried out on Mr. Stroudley's machine (Fig. 9), where A is a micrometer screw capable of measuring to 0·0001 inch, carried by a small bracket fastened to the brass, but electrically insulated from it by paraffined paper.

FIG. 9.

B and C are terminals for attaching insulated wires to a weak voltaic cell and galvanometer. When the micrometer touches the shaft the galvanometer is deflected; this is set so that there is contact when the shaft is at rest, but immediately it is put in motion the brass with the micrometer is raised and the circuit is broken; the screw is again set to just touch the shaft, when the micrometer indicates the height to which the brass has been raised. The amount was found to vary with the efficiency of the lubrication. With a pad-lubricator it was raised to 0·0013 inch on first starting, and as the films became better developed the friction decreased and the brass was ultimately raised 0·0029 inch. It was found by Mr. Tower that there was an immense pressure of oil between the brass and the journal, equivalent at a certain point to more than double the nominal load per square inch.

In making a similar experiment with Mr. Stroudley's machine,

the Author found that ordinary lubrication with a pad failed to give any pressure on the gauge, but if the pad was dipped in oil and applied in a dripping condition, the pressure immediately rose, and gradually sank as the oil-supply diminished; thus the pressure-gauge became a good indicator of the efficiency of the lubrication. In the same experiment it was found that the coefficient of friction was about 25 per cent. lower when the oil-hole on the top of the brass was closed with a screwed plug, thus indicating that the oil escaped at the apex of the bearing, and so prevented a cushion or film of oil being effectually formed.

With well-lubricated surfaces the amount of wear is extremely small, even at high surface velocities; for instance, on the Brighton railway there are many cast-iron eccentric straps working on cast-iron sheaves, which have been running constantly for twelve or thirteen years without requiring the slack to be taken up; their surface velocity is about 900 feet per minute, representing in thirteen years a distance of at least 100,000 miles passed over by the surfaces. This excellent result is due to the thoroughly good system of lubrication adopted.

DRY SURFACES.

The following laws, which are based upon the results of modern experiments, appear to govern the friction between dry surfaces:—

1. The friction between dry surfaces under moderate loads and low velocities, varies directly as the normal pressure between them.
2. The normal pressure remaining unchanged, the friction is independent of the area in contact.
3. It is always greater on the reversal of direction of sliding.
4. It sensibly diminishes with a rise of the temperature.

1. In the "Galton-Westinghouse" experiments it was found that with velocities below 100 feet per minute, and with low pressures, the frictional resistance varied directly as the normal pressure; but when a velocity of 100 feet per minute was exceeded, the coefficient of friction greatly diminished; from the same experiments Professor Kennedy found that the coefficient of friction for high pressures was sensibly less than for low.

2. This law is best demonstrated by arranging an inclined plane of suitable material, and placing on it several bodies of the same weight and similar material, but with different areas in contact;

when a sufficient inclination is given to the plane, they will all start sliding together; thus the-area in contact does not affect the coefficient of friction.

3. This law can be demonstrated by attaching a string to a sliding body on a horizontal plane; the string passes over a grooved pulley to a scale-pan in which are placed weights just sufficient to made the body slide; but if the body be turned round so that its direction of sliding is reversed, the original weights will be insufficient to cause sliding, showing that the friction is greater. This law is also true for lubricated surfaces.

4. In the experiments on brake-blocks, it was found that they became considerably heated after successive applications, and at the same time the coefficient of friction sensibly diminished.

Possibly this may be the reason why the friction diminishes with increased pressures, for the heat generated by friction varies as the normal pressure.

The theoretical consideration of "dry friction" is of a much more complex nature than that of lubricated surfaces, but if it be assumed as a basis that all the surfaces of solid bodies resemble in structure the surface or pile of velvet, many, if not all the difficulties will be easily overcome. However smooth the surfaces may appear, a pile will still be left; for as the original surface is worn away, particles of metal are torn from the main body, each of which will leave its own jagged hole, and constitute a fresh pile as the old one is removed. An illustration of this is seen when a piece of wood is filed transversely to the grain; as long as the filing is continued a rough surface is left. The pile will necessarily partake of all the physical properties of the metal, its tenacity, elasticity, coarseness of grain, &c. The latter property will determine the degree of fineness, or "pitch of the pile," which is simply the relative number of fibres or piles per unit of area.

When two such surfaces are pressed together, the pile will become partially flattened, and will not leave a perfectly smooth surface, but one consisting of minute indentations and projections, the latter on one surface fitting into the former on the other. Hence, before any sliding motion can take place, the projections on the one must mount up and pass over those on the other, which constitute a series of minute inclined planes. But before this motion can take place, a force must be applied to the sliding body, one component of which acts in opposition to the normal pressure; the force required to make a body slide up these inclined planes is the resistance of friction, hence the greater the normal pressure, the greater is the resistance to sliding. If the normal pressure be

too great, abrasion takes place, and the resistance is greatly increased, because the force now required to produce sliding must be sufficient to tear the pile or fibres from the metal. Fig. 10 illustrates how the pile causes the frictional resistance, the pile being highly exaggerated to show the effect more clearly. A and B are two masses of metal, of which A slides over B; now it is evident that before any sliding can take place, A must be vertically raised through the distance $\alpha \beta$; then while sliding is taking place, A is being constantly raised and allowed to fall through $\alpha \beta$. The force required to maintain this motion is the frictional resistance; the blow given at each fall is converted into heat, and hence the heat caused by friction is simply due to the impact of the bodies.

FIG. 10.

The total amount of work done against frictional resistance may be expressed thus—

Let n = the number of projections, piles, or fibres per lineal inch.

Let the space $\alpha \beta$ (Fig. 10) = $\cdot \theta$ inch.

Let the normal pressure = ϕ lbs.; then the work done in making A slide through 1 inch is—

$$W = \frac{n \times \theta \times \phi}{12} \text{ foot-lbs. of work.}$$

In Fig. 11, let xy represent an inclined plane, with a body Z just beginning to slide by its own weight, then $\tan \phi$ will be the coefficient of friction; now it is evident that the pile must be flattened by the sliding body, so that the side of each fibre is level, or slightly lower at the tips, hence it follows that the coefficient of friction is the tangent of the angle which the side of each loaded fibre makes with the surface of the plane on flat surfaces.

It will now be seen why the friction is independent of the area in contact, the normal pressure remaining unchanged, as the resistance is only dependent upon the height $a\beta$. When the direction of sliding is reversed, the pile, which is already flattened in the original direction, must describe the arc of a circle before it can be flattened in the reverse way (Fig. 12), and then the vertical distance $a\beta$ is increased to mn , which will account for Law No. 3.

If the temperature of the surfaces is high, the pile is more pliable, and consequently becomes more flattened, which reduces the height $a\beta$, with a corresponding diminution of friction.

When the velocity of sliding is very small, the projections on one surface sink completely into the indentation on the other;

FIG. 11.

FIG. 12.

but when the velocity is increased, the tips of the fibres only come in contact, as there is not sufficient time for the one to sink its full depth into the other, which again reduces the vertical height $a\beta$; but in the case of high velocities of revolving bodies, another force comes into operation; so-called centrifugal force acts on the pile and stiffens it, as it tends to fly from the centre, for the same reason that revolving brushes are always stiffer at high velocities than at low, this stiffening increases the friction, as each pile has to be flattened before passing under the bearing.

The coefficient of friction is always higher with similar, than with dissimilar metals; the reason of this may be seen from Fig. 13; in the second case, the vertical height $a\beta$ is considerably less than in the first.

The problem, to find the work absorbed by friction, is one

which often occurs in practice; it may therefore be useful to consider the method.

FIG. 13.

Let P = normal pressure in lbs.;

u = coefficient of friction, namely, the ratio of the resistance to the load;

s = space in feet through which sliding takes place;

t = time in minutes during „ „ „ „

n = number of revolutions per minute;

v = velocity of sliding, in feet per minute;

a = number of square inches of surface in contact;

d = diameter of journal in inches;

W = work absorbed in foot-lbs.

Then for flat surfaces $W = P \times u \times s$.

$$\text{HP.} = \frac{P \times u \times v}{33,000}.$$

Cylindrical journals per revolution— $W = \frac{P \times u \times 3.1416 d}{12}$.

$$\text{HP.} = \frac{P \times u \times 3.1416 \times d \times n}{12 \times 33,000}.$$

The frictional resistance of a sliding body is expressed thus:—

$$P \times u.$$

Frictional resistance per square inch:—

$$\frac{P \times u}{a}.$$

To calculate the HP. absorbed by friction in a train—

Let N = the number of square inches (nominal) of bearing-surface in the whole train;

FR = average or mean frictional resistance per square inch on all the journals;

JS = average or mean velocity in feet per minute of all the journals.

$$\text{Then HP.} = \frac{N \times F R \times J S}{33,000}.$$

The pull on the draw-bar due to journal friction per ton weight of train—

Pull in lbs. = $\frac{u \times 2,240}{r}$, where r is the ratio of the radius of wheel to the radius of journal.

In calculating the load on the journals of railway-axes, it must be borne in mind that the dead-weight of the vehicle on the brass is only a part of the total load; the other factor of total load is the rolling-resistance of the wheels in the direction opposite to that in which the train is travelling; the amount of this second factor is at present unknown, and can only be ascertained by a special experiment; but however great this pressure may be, the brass does not wear in that direction, but always on the forward side of the brass. The same observation has been made in marine-engine journals, which always wear in exactly the reverse way to what they might be expected. Mr. Stroudley thinks this peculiarity is due to a film of lubricant being drawn in from the under-side of the journal to the aft part of the brass, which effectually lubricates and prevents wear on that side; and that when the lubricant reaches the forward side of the brass, it is so attenuated down to a wedge-shape that there is insufficient lubrication, and greater wear consequently follows.

The Author was engaged by Mr. W. Stroudley, M. Inst. C.E., in carrying out these experiments on friction, and is greatly indebted to him for permission to place the results arrived at before the Students of the Institution.

The communication is illustrated by several diagrams, from which the Figs. in the text have been engraved.