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JAMES CHARLES INGLIS, President,  
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# “Construction and Wear of Roads.”

By HENRY REGINALD ARNULPH MALLOCK, F.R.S.

SINCE the introduction of soft tires and mechanical propulsion for vehicles, the conditions to be satisfied on good roads have been considerably altered. The new conditions are in some respects more, and in others less, exacting than when traffic was conducted entirely by animal draught and on iron-tired wheels.

As the subject of the improvement of roads and the prevention of dust is a matter of great interest at present, the Author has noted in this Paper the conclusions he has formed in the course of the last 15 years, from observation on many thousand miles of different classes of road in various parts of the United Kingdom and elsewhere. These conclusions have been generalized as far as possible, in order to bring out the underlying principles rather than to make any specific recommendations for particular cases. Since writing the body of the Paper, the Author has looked through a large quantity of the literature on the subject, and has found that in nearly all cases the questions are treated from a strictly practical point of view. This is not to be wondered at, as the problems involved, though difficult, are not of a kind to offer much attraction to the physicist. It is often useful, however, to have some simple, even if incomplete, theoretical treatment of a subject, provided that the theory is correct as far as it goes, and is kept within bounds by comparison with actual observations. It is chiefly with such simple theory that the present Paper is concerned.

The divisions of the subject may be classified as follows :—

Foundations.

Surface : wear caused by various classes of traffic ; effect of speed.

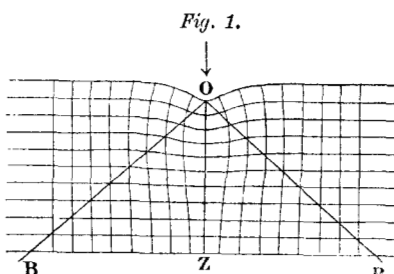
Drainage : cross section of roads ; effects of rain and watering.

Formation and diffusion of dust.

## FOUNDATIONS.

Whatever may be the geological character of a district, it is necessary, except in a very few cases, to interpose a considerable depth of foundation between the surface which carries the traffic and the natural ground: first, in order that repairs may be made; and, secondly, to fulfil the following conditions:—

- (a) The foundation must be strong enough at each level to resist the local pressures without crushing or permanent set.
- (b) It must be thick enough to distribute the local pressure on the upper surface over such an area on the lower surface that the ground on which it rests is not disturbed beyond its elastic limit.
- (c) It should facilitate the escape of such water as may percolate through the surface, though in the case of roads with a waterproof surface this becomes a secondary matter.



FORM OF DEPRESSION IN A THICK  
ELASTIC SOLID.

The intensity of the pressure caused by traffic becomes greater as the surface is approached, and therefore, in order just to fulfil conditions (a) and (b), either the material near the surface must be harder there than at lower levels, or it must have a greater elastic limit. If the material is equally hard throughout, the surface will yield less under the load, and the load in consequence will be

carried on a smaller area, the intensity of the surface pressure being thereby increased. Thus too rigid a foundation may cause the surface to break up, as well as one which is too soft.<sup>1</sup>

It may be well to consider here in rather more detail the action on the ground of a load covering a small area of its surface.

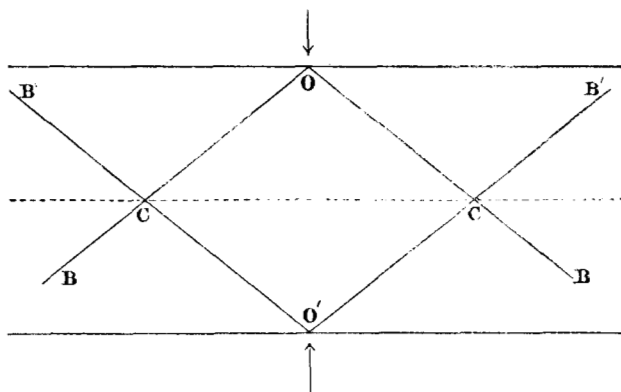
It has been shown by Professor J. Boussinesq and others<sup>2</sup> that if a load is placed at a point on the flat surface of a thick elastic solid the surface is everywhere depressed, and that the form of the depression is hyperbolic in section, as shown in *Fig. 1*. The direction of the

<sup>1</sup> The generally bad and loose condition of roads where hard natural rock comes to the surface is a case in point; or again if a road has to pass over steel girders or masonry, either a considerable depth of softer material must be placed between the road-surface and the bed, or the surface itself must be capable of considerable distortion without rupture.

<sup>2</sup> See A. E. H. Love, "Mathematical Theory of Elasticity." Cambridge, 1906.

force at any point in the ground is along the line joining that point with the place at which the load is applied. The displacement at any point  $P$  is inversely proportional to its distance from the load, but varies also in a rather complex way with the angle  $P O Z$ , which the line joining  $P O$  makes with the vertical. The horizontal component of the displacement is towards the axis  $O Z$  for all points outside a cone  $O B$  and away from  $O Z$  for all points inside it; and the stresses thus tend to dilate all the material outside the cone and to compress all within it.<sup>1</sup> When the load is applied over a small finite area instead of at a point, the form of the displacement is slightly altered, but the general characteristics are unchanged. The angle  $B O Z$  may range from  $52^\circ$  to  $90^\circ$  according to the nature of the material.<sup>2</sup>

Fig. 2.



The result of the presence of a hard stratum at some distance below the road-surface can be indicated as follows:—

Imagine a plate of thickness  $2d$  (Fig. 2), and let equal and opposite forces act normally to the surface at each end of a perpendicular through the plate. The middle surface in this case, from symmetry, remains a plane, the normal displacements there neutralizing one another. The horizontal displacements however, due to both forces, are in the same direction within the volume bounded by the two

<sup>1</sup> The dry patch which, for a short time, is seen to surround the footsteps of anyone walking on hard wet sand, is one of the consequences of this dilatation.

<sup>2</sup> The angle depends on Poisson's ratio (namely, the ratio of lateral contraction to longitudinal extension) for the material. This ratio must lie between  $\frac{1}{2}$  and 0. For most materials it lies between  $\frac{1}{3}$  and  $\frac{1}{2}$ , which would bring the angle of the cone between  $58^\circ$  and  $68^\circ$ .

cones  $O B$ ,  $O' B'$ , but in opposite directions in the compartments  $B C O'$ ,  $B' C O$ . The upper half of the figure may be considered to represent approximately the case of an elastic plate of thickness  $d$  resting on a perfectly hard plane, and this result indicates that the stresses inside the cone are intensified by the presence of the hard surface, while outside they are to a certain extent diminished.

Quantitative results could not be given without the use of symbols, but what has been said is sufficient to indicate the necessity in road-making of laying a certain minimum depth of elastic foundation over hard ground. The actual thickness required in any particular case depends on the material used. A very small depth of india-rubber is sufficient to coat steelwork or hard stone, but many inches of macadam would have to be used for the same purpose. Thus on the whole, when the ground is soft, sufficient foundation is required to distribute the traffic-load, and on hard ground it must be thick enough not to be disturbed by the increased stress caused by the presence of the unyielding bed. The ideal foundation—the foundation, that is, which will just do the work required of it—should form a bed the properties of which change gradually and continuously from the natural ground to the surface carrying the traffic.

#### SURFACE OF ROADS.

At the present time five distinct types of surface are in use in this country, namely:—

Blocks of stone, or sets.

Wooden blocks exposing the end grain at the surface.

Asphalt.

Macadamized roads.

Surfaces of broken stone similar to macadam, but with a binding material of some viscous material such as tar or its compounds.

Each of these types shows some peculiarities in the way in which it is worn by traffic. The surface of stone sets, even if perfectly flat when these are laid, would soon cease to be so under the influence of heavy loads carried by iron-tired wheels. The arc of contact between such wheels and the stone, as will be shown later, is much smaller than the width of a single stone, and the stones themselves are never laid in close contact. The consequence is that, as the surface of contact of the tire approaches the edge, the intensity of pressure increases and the stone is either crushed or splintered. The edges of stone sets, therefore, soon become rounded, and the surface, assumed plane at first, becomes a succession of flat-topped ridges. The vertical accelerations to which a body passing over such a ridged surface

is subject tend to increase the pressure at the bottom of the valleys and to decrease it at the summit, and thus the continued action of traffic carried on iron tires has the effect of further developing the ridges. The ridge-like structure is very characteristic of old stone paving, and it greatly increases the tractive power required for haulage, partly on account of the work done in propagating vibrations in the ground, and partly from the vibration set up in the vehicle itself. The motion of the latter, in fact, is the same as if it were moving over a flat surface on polygonal wheels.<sup>1</sup>

The governing factors as to the speeds possible on such pavements are: first, the period of vibration of the body and load on the springs of the vehicle; secondly, the period of the wheels themselves (and the parts which move with them, axles, etc.) on the springs. If either period approaches the time which is taken in crossing from one ridge to the next, excessive vibration will be set up and the tractive resistance will rise. Since the load carried is generally much in excess of the weight of the wheels and their fittings, the first-mentioned period will be the longer; and thus, if traction experiments were made on a ridged pavement, there would appear two humps on the resistance-speed curve corresponding with the two periods.

The blocks of wood employed in paving are very similar in size and proportions to the stone sets. In this country several kinds of wood have been tried. The greater part is deal of various kinds, but the hard Australian woods, jarrah and karri, have also been used.

The surface wear depends largely on the softness of the wood. Deal retains a fairly even surface under traffic, but is liable to wear into hollows, and occasionally single blocks fail, forming cavities which enlarge owing to the excess of pressure brought to bear by the wheels on the edges of the surrounding blocks. The hard woods are not so liable to this, but wear more after the fashion of stone pavements, and the harder the wood the more is this the case. There are, or were, several roads paved with hard wood in the south of London, which it would have been difficult to tell by the eye from stone after they had been laid for several years.

As regards the tractive effort required to haul a given load over a worn wooden pavement, the softer wood should be the superior; for although the wear of its surface is more rapid than with hard woods,

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<sup>1</sup> The Author remembers seeing a lorry, on which was a large Cornish boiler, pass from asphalt (where the horses had been going at a moderate trot) to granite sets, with the result that before the speed could be reduced the boiler was dismounted and fell sideways on the road.

the surface itself remains in general smoother, and the hollows, though often deep, are not steep-sided.

The coating of gravel which is now spread over wood pavements when first laid down appears not only to make them less slippery, by reason of the grit left embedded in the wood when the mass of gravel has been removed, but also to add to the life of the pavement by providing a kind of hard scale as a protection for the woody fibre.

The asphalt pavements, which are mixtures of finely broken stone and pitch, probably require less tractive effort for haulage than any others, and when clean they are not slippery, whether wet or dry. Their defect is that the viscous surface is driven into lumps and ridges by hard tires, and the same cause, especially where the thickness has been reduced by wear on the projections, has the effect of breaking up the surface. In addition to this, the hardness of the material is much affected by temperature, and the mud formed by the mixture of horse-droppings and the asphalt detritus is more slippery than any mud which does not contain clay.

The breaking up of the asphalt surface is an example of the effect of a hard and unyielding bed placed under an insufficient thickness of protecting surface. The insufficiency of thickness may be due to the asphalt mixture being too brittle, but more generally to a good asphalt having been worn or squeezed so thin as to be unable to bear the shear which traffic-loads impose upon it. In some cases the Author has seen a broken surface result from a failure of the concrete bed, but this is probably a comparatively rare occurrence.

In macadamized roads the foundation is of broken stone, and the surface consists of rather smaller broken stone, mixed with a certain amount of softer binding material.

Hard tires wear out such roads in two ways: first, by the direct crushing of the projecting stones; and, secondly, by causing the surface stones to rub against one another. The first cause is most operative on roads in good condition, but when once the surface becomes loosened the second is equally potent.

Of late years roads have been laid which are similar to macadam roads as regards structure, but have a surface layer with a binding material of tar-compounds. Such roads appear to combine many of the advantages of asphalt with the comparative cheapness of broken stone, and though they are more expensive initially than ordinary macadam, their wear and cost of upkeep are said to be considerably less.

The large limit of elasticity which these binding materials give to the surface not only lessens the destruction of the surface by

crushing, but also prevents it from becoming loose or broken; and in both these ways it greatly reduces the amount of dust which would be formed if earthy binding material took the place of the tar.

Many forms of such road-surfaces have been proposed and tried, some containing the tar-compounds to a depth of 2 inches or 3 inches, and others merely having the tar applied in the form of spray to the newly-formed and dry surface, into which it sinks for a small depth. All these surfaces have given favourable results, but in judging of their practical utility the higher cost of the more deeply tarred coating has to be set off against its longer life. The condition essential to the success of all these tarred roads seems to be that the metalling must be capable of holding the tar firmly.

*Pressure and Wear caused by Iron and other Tires.*—When a loaded wheel rests or rolls on the ground, the mean intensity of the pressure between the two is measured by the load divided by the area of contact, and with solid tires the maximum intensity is one-and-a-half times the mean.

In order that the circular arc of the tire may touch the flat road over a finite area, both the tire and the road-surface must be deformed. If both surfaces are equally deformable, the common curve in which a wheel of radius  $r$  will touch a plane is the arc of a circle of radius  $2r$ . If the substance of the tire is harder than the ground, the latter is more deformed than the wheel, and the arc of contact has a radius of curvature less than  $2r$  but greater than  $r$ . If the tire is softer than the ground, the radius of curvature of the arc of contact may bear any value between  $2r$  and infinity.

In all cases the area of contact must be sufficient to bear the load by elastic reaction, and if, in order to attain such an area, the road-material has to be deformed beyond its elastic limit, a certain depth of road-surface is destroyed every time a wheel rolls over it.

The arc<sup>1</sup> of contact between a cylinder and plane is  $\frac{c}{r^{\frac{2}{3}} b^{\frac{1}{3}}}$  where  $r$  is the radius,  $b$  is the length of the cylinder and  $c$  is a constant depending on the elasticity of the materials. In the case of a wheel  $r$  will be the radius of the wheel and  $b$  the width of the tire.

Table I shows the order of the area of contact, and the intensity of pressure to be expected when wheels of various radii, 1 inch

<sup>1</sup> See p. 169 as to the sense in which "arc" is used here.—SEC. INST. C.E.

wide, carry a load of 1 ton on various kinds of material used in paving, where

L denotes the length of the arc of contact.

$p$  „ „ mean pressure per square inch.

P „ „ maximum pressure per square inch.

TABLE I.—LENGTH OF CONTACT AND INTENSITY OF PRESSURE BETWEEN VARIOUS PAVING MATERIALS AND A STEEL TIRE 1 INCH WIDE CARRYING A LOAD OF 1 TON.

Radius of Tire.	Steel Surface.			Granite.			Jarrah Wood.			Deal.			Asphalt.		
	L	$p$	P	L	$p$	P	L	$p$	P	L	$p$	P	L	$p$	P
Ins.	In.	Lbs.	Lbs.	In.	Lbs.	Lbs.	In.	Lbs.	Lbs.	In.	Lbs.	Lbs.	In.	Lbs.	Lbs.
24	0·68	3300	4950	0·74	3000	4500	0·81	2780	4170	0·95	2350	3520	1·18	1900	2350
18	0·625	3600	5400	0·69	3250	4900	0·74	3020	4550	0·87	2560	3820	1·08	2080	3120
12	0·54	4150	6200	0·59	3800	5700	0·64	3500	5250	0·75	3000	4500	0·93	2480	3720
6	0·41	5400	8100	0·45	5000	7500	0·49	4500	6750	0·58	3850	5750	0·74	3000	4500

The experiments from which the results in Table I are derived were made by placing hard-steel arcs of 24 inches and 6 inches radius, respectively, on flat surfaces of the various materials tested, with a thin strip of carbon tissue paper and copying-paper interposed, the load being then applied in a hydraulic press. The blackened copying paper showed the area over which contact had prevailed; and since the steel used was much harder than any of the materials tested, its curvature remained practically unaltered.

It was not practicable to make similar experiments on a macadam surface. The maximum pressure, however, for such a surface would be much the same as for a solid pavement of the stone used.

In the case of solid india-rubber tires, the distribution of pressure over the area of contact with the ground is similar to that for iron tires, and the maximum pressure is half as much again as the mean. The softness of the tire, however, makes the area of contact so much larger that the mean pressure is greatly reduced. Some measurements, given in Table II, were made on solid tires using carbon tissue paper as the means of record, and show that the contact-area of each tire of the motor-omnibuses<sup>1</sup> running in London is 13 square inches approximately, giving a mean pressure of 120 lbs. to 140 lbs. per square inch. For a wheel of the same radius with iron tires 2 inches wide the area of contact deduced from the formula

<sup>1</sup> The Author has to thank the Joint Managers of the London General Omnibus Company for having given him the opportunity of making these measurements.



previously given would be 0·6 square inch, and the mean pressure would be 3,000 lbs. per square inch.

TABLE II.—AREA OF CONTACT BETWEEN THE GROUND AND THE SOLID INDIA-RUBBER TIRES OF A MOTOR-OMNIBUS.

The area of contact *A* is an oval, *a* denoting the long axis, and *b* the short axis, of the oval.

Load on each front wheel = 0·84 ton nearly.

“ “ “ back wheel = 1·46 “ “

<i>Front Wheel.</i>					
	<i>a</i>	<i>b</i>	<i>A</i>	<i>p</i>	<i>P</i>
	Inches.	Inches.	Sq. Ins.	Lbs.	Lbs.
New tire . .	6·9	2·5	13·5	140	230
Worn tire . .	5·7	3·4	14·6	129	200

<i>Back Wheel.</i>										
Outer Tire.						Inner Tire.				
	<i>a</i>	<i>b</i>	<i>A</i>	<i>p</i>	<i>P</i>	<i>a</i>	<i>b</i>	<i>A</i>	<i>p</i>	<i>P</i>
	Ins.	Ins.	Sq. Ins.	Lbs.	Lbs.	Ins.	Ins.	Sq. Ins.	Lbs.	Lbs.
New tire . .	7·6	2·2	12·6	129	200	7·65	2·1	12·6	129	200
Worn tire . .	5·7	3·16	14·2	114	180	5·5	3·35	14·4	113	179

Probably the elastic coefficient of the various classes of india-rubber used for solid tires varies considerably, but even with the hardest specimens it does not seem likely that the mean pressure on the road ever exceeds one-twelfth part of the mean pressure which iron tires would give with the same wheel.

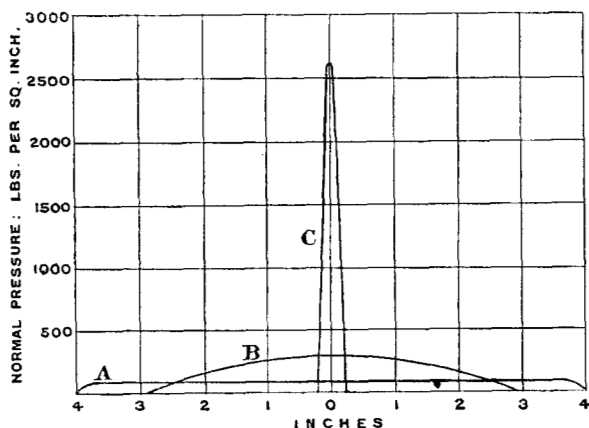
With pneumatic tires it is nearly correct to take the pressure on the ground as uniform over the whole area of contact, and equal to the air-pressure in the inner tube. Thus the area of contact is obtained by dividing the load by the internal pressure. It can be shown that in a well-inflated tire (that is, where the inflation is sufficient to prevent any great change of shape except where the tire touches the ground) the area of contact is an ellipse, whose major and minor axes are proportional to the square roots of the principal radii of curvature, that is to the square roots of the radius of the wheel and the radius of the tube. If *a* and *b* are the semi-axes of this ellipse, then  $\pi a b P = W$ .

As an example, suppose that *P* is 60 lbs. per square inch, and the

wheel carries  $\frac{1}{2}$  ton or, say, 1,200 lbs., then the area of contact is 20 square inches. Further, if the diameter of the wheel is taken as 30 inches, and that of the tube as 5 inches, then since  $\frac{a}{b} = \frac{\sqrt{30}}{\sqrt{5}}$  or 2.45, and  $\frac{\pi a^2}{2.45} = 20$ , therefore  $a = 3.95$  inches. Thus the area of contact is an ellipse about 8 inches long and 3.2 inches wide.

Of course the smaller the air-pressure in the tire the less intense is the pressure on the road. A low air-pressure therefore is good for the roads, but on the other hand, it is bad for the tires, because

Fig. 3.



INTENSITIES OF PRESSURE ON ROAD WITH A LOAD OF  $\frac{1}{2}$  TON.

- A. Pneumatic tire,  $\frac{1}{2}$ -inch tube, air-pressure 80 lbs. per square inch.  
 B. Solid rubber tire, 18 inches radius, 1.5 inch wide.  
 C. Steel tire, 18 inches radius, 1.5 inch wide.

of the increased distortion of the tire-fabric. The intensity of the pressure with pneumatic tires is in any case so low that the ratio of air-pressure to load, which will at some future time be taken as the standard, will be settled rather with reference to the tire than to the road. In Fig. 3 a comparison is given of the intensity of the pressures on the road due to the same wheel fitted with iron, solid india-rubber, and pneumatic tires, under different loads.

These pressures are the statical pressures which would be exerted by a wheel at rest or moving very slowly. A brief reference will now be made to the changes in intensity which are caused by speed.

It is clear that if a wheel rolls over a flat surface, and has such a radius and carries such a load as to cause elastic stresses only, the speed of rolling can have no effect. When, however, the surface of the ground is rough or undulating, the effective load varies, and the variation must increase as the square of the speed as long as there is continuous contact between the wheel and the surface. If the speed over an undulating surface is high enough to cause the wheel to leave the ground in places, the impact when contact is again made causes pressures of great intensity for a short time. The same may be said of the pressures exerted on small abrupt prominences, such as loose stones, which are impinged upon by the tire at some distance in advance of the vertical line through the axis.

The downward velocity of a tire of radius  $r$  rolling with velocity  $v$  on a prominence of height  $h$ , is  $v\sqrt{\frac{2h}{r}}$ , and the force of impact will vary as  $v^2\frac{2h}{r}$ , showing that for a given velocity of the vehicle the momentary pressure varies inversely as the radius of the wheel, and hence that small wheels with hard tires are, in nearly the same proportion, more destructive than large wheels. With pneumatic tires the case is different. The intensity of the pressure can never differ greatly from that of the air-pressure in the tube, and the result of vertical acceleration is to alter the area of contact, but not the pressure per unit of area.

The general expression for the pressure between a wheel and the ground, taking into account all the circumstances as to velocity, roughness, and nature of the surfaces, presents no theoretical difficulties; but it is sufficient here to say that the destructive effect cannot be less than proportionate to the square of the speed, with a constant deducted, and it may be greater when the speed is sufficient to make the contact discontinuous.

Very few substances in nature are perfectly elastic. In nearly all cases, if a substance is compressed and then allowed to expand again, the pressures at corresponding stages of compression and expansion are different and are less during expansion than during compression, the difference in general being a function of the time as well as of the displacement. As far as the road-surface is concerned, the effect of this property is to change not the intensity but the distribution of pressure over the area of contact, the pressure being greater in the front half of the area where the tire is approaching the ground than in the rear half where the tire is rising. On the wheel the difference gives rise to a force, acting against the direction of motion, and increasing

with the speed according to some function which is not known at present.

Some of the materials used in road-making are more or less viscous, that is, the displacement caused by a given force continues to increase with the time for which it is applied. In perfectly viscous materials any force, however small, will cause unlimited distortion if the time of action is prolonged. In the asphalt used in road-making, which consists of hard particles bedded in a viscous substance, the distortion ceases when it has brought the hard incompressible parts into contact. On any partially viscous road the mean wheel-pressure decreases as the speed decreases, because of the increased area of contact which the lower speed allows. The tractional resistance, however, will decrease with increase of speed because of the less work done in distortion.

In estimating the resistance to traction, both the want of resiliency and the viscosity must be taken into account, and the smoother and more even the surface of a road is, the larger will be the proportion of the resistance for which these causes are responsible. On railways these two forces probably cause a very appreciable part of the total resistance, and, as the Author pointed out during the discussion of a Paper by Mr. J. A. F. Aspinall, M. Inst. C.E., out of the total resistance measured by the latter in many careful experiments, less than 40 per cent. was accounted for by recognized causes, i.e., constant friction and air-resistance.<sup>1</sup> On ordinary roads, however, by far the largest part of the resistance (as far as iron-tired vehicles are concerned) is due to the destruction of the surface by the high pressure developed over the area of contact; and where the road-surface is loose, even pneumatic tires may cause wear, not by the pressure of the tire on the road, but by making the loose parts grind on one another.

One other source of wear by pneumatic tires must be mentioned. The length of the area of contact is less than the length of the arc of the circle of which it is the chord by the quantity  $2r\left(\frac{\theta}{2} - \sin \frac{\theta}{2}\right)$ . Hence the mid-length of the india-rubber in the area of contact is in longitudinal compression. This compression takes place during the time occupied by the surface in passing from a position where it is free from disturbance to a small distance inside the boundary of the area of contact. Under the full pressure, on dry surfaces at any rate, friction is then sufficient to prevent slip. The compression is as quickly relaxed where the

<sup>1</sup> Minutes of Proceedings Inst. C.E. vol. clviii, p. 369.

surface of the tire leaves the ground. During these two small intervals, however, there is a certain amount of sliding between the tire-surface and the ground, which may cause wear. It may be compared with the action of the bristles of a brush.

#### DRAINAGE.

*Effect of Rain and Watering on the Wear of Roads.*—In considering this part of the subject it is convenient to divide roads into two classes, according as the roads are waterproof or are permeable to moisture.

On wood, asphalt, and tarred surfaces, which form the first class, wetness has little primary effect on wear; but such effect as there is is bad, in the case of wood because it keeps the surface soft and less able to bear high pressure without damage, and in the case of asphalt and tarred surfaces because it facilitates, by acting as a lubricant, the grinding action of traffic on any loose material which may be present.

On ordinary macadam the direct effect of moisture is much greater; heavy rain, and, still more excessive watering, reduce the surface to a succession of transverse hills and valleys, which tend to deepen each time that water is carried off by them. The ill-effect of watering is so apparent that it is generally possible, on approaching a town, to recognize by the bad surface of the road the limits to which the local water-carts operate. But the deepening of existing hollows in a road is not due only to the action of running water. The hollows remain damp and soft longer than the ridges, and in consequence are more cut up by wheels.

The transverse ridges alluded to are often very prominent and exceedingly regular in pitch for long distances, and it would be interesting to determine what settles the interval between them, which is generally 3 or 4 feet. Where such regular spacing occurs, the position of ridge and valley must be settled very early in the life of the road, and in some cases, at any rate, it might be due to the variable outflow from a horse-drawn water-cart, which would deepen any hollows existing where the excess of water fell. That the flow must vary between each step of the horse is certain, and in a case where the depth of the water in the tank was such as to make its natural period the same as the time taken for each step, the Author has seen the flow become almost discontinuous.

In other cases it is possible that the circumstances of the original formation and rolling of the road may have caused a periodic

irregularity of surface. If a roller pushes the road-material in front of it, which would happen when the pressure was too high or the road-material was too soft, two cases present themselves. If the material so pushed horizontally retains its average texture, and its resistance to deformation becomes neither greater nor less in consequence, the accumulation will go on till the virtual slope up which the roller works reaches a certain value, after which the conditions remain constant and the rolled surface is flat (this is what occurs in rolling armour-plate, for instance). On the other hand if, as may well happen when the road material is too wet, the part which is forced horizontally becomes less easy to distort, the roller in the course of time will have to climb over the hard hill it has accumulated in front of it, and this process will be repeated at regular intervals, leaving a succession of ridges. If this is the origin of the road-ridges, the factors determining their distance from each other must depend upon the radius of the roller, upon the pressure, and upon the variation of resistance to distortion offered by the material as it is pushed forward.

An analogous cause operates when a cutting tool acts on many metals (notably iron and steel) and produces the step-like effects which are often conspicuous in the shavings removed.

In all roads, especially such as are waterproof, the cross section of the surface plays an important part, if not on the wear of the surface, at any rate on the comfort and convenience of the users. If the higher part is too flat it becomes flooded in wet weather, and if the ordinary barrel-shaped section is given to a wide road the slope at the sides is inconveniently steep.

It is worth while to see what the cross section must be if (i) the water is to have a uniform depth; (ii) the surface flow is to have a uniform velocity.

If  $v$  and  $v'$  are the velocities of the surface flow and the rainfall<sup>1</sup> respectively, and if  $x$  is the distance of a point P on the surface from the watershed, and  $h$  is the depth of the surface current; then, on a waterproof road, the relation  $v'x = vh$  must hold as soon as the drainage balances the rainfall.

Different suppositions regarding the relation between the gradient ( $\theta$ ) at  $P_1$ , and between  $v_1$  and  $h_1$  may be made according to the condition of the surface and its cleanliness.

If the surface is clean, smooth, and free from local irregularities,  $v$  will be proportional to  $\theta h$ , and this leads to a form of cross

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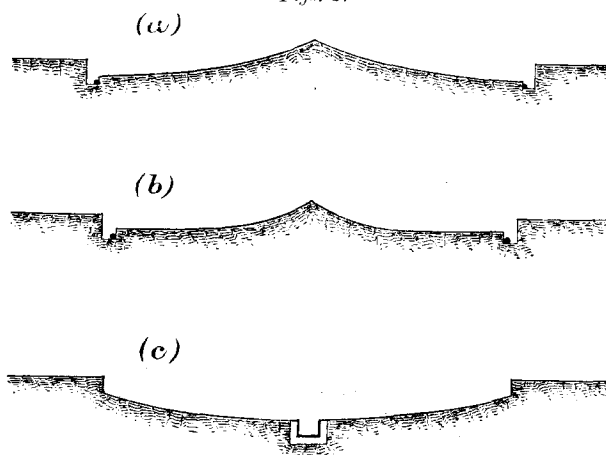
<sup>1</sup> This is of course very small. An inch a day, which is moderately heavy rain in this country, is only about  $\frac{1}{80,000}$  inch per second.

section which for (i) is practically the arc of a circle, and for (ii) a logarithmic curve, *Fig. 4a*.

In the case of ordinary road-surfaces with irregularities which cause the water to run off in separate lateral streams, it would be more nearly true to take  $v$  as proportional to  $\sqrt{\theta h}$ . This supposition leads to a cubic parabola as the cross section in case (i) *Fig. 4b*, and for case (ii) to a logarithmic curve very similar to *Fig. 4a*.

As far as the removal of mud, etc., from the surface goes, the sections which give uniform velocity are to be preferred, but it is plain that such sections as are shown in *Figs. 4a* and *4b* are not practical ones. There seems no reason, however, why such a section as is shown in *Fig. 4c*, which is merely *Fig. 4a* with the halves transposed,

*Figs. 4.*



should not be tried, and the Author believes there is at least one practical road-surveyor who considers that a road lower in the centre than at the sides would be the most suitable form. In country roads the expense of the central drain would be prohibitive, but in towns with a proper system of sewers this objection does not apply. The central drain would be covered by a continuous grating, and the floor of this drain would have a moderate gradient towards the catchpits.

There can be no question that such hollow roads would tend to keep the footpaths free from mud. The ordinary form of road, which drains at the sides, accumulates all the dirt and mud in the place where it can be most easily splashed over foot-passengers. The catchpits occur at considerable intervals, and the longitudinal

gradient which carries the drainage to them can differ little from the general gradient of the road: the result is that, on the level, the gradient required to give the flow is only obtained by the varying depth of the stream in the gutters. This depth, as most people know to their cost, is often to be measured in inches. Besides causing an accumulation of liquid mud close to the foot-pavements, another disadvantage of the small longitudinal gradient is that the stream in the gutters is often deep enough to float or wash solid dirt to the neighbourhood of the gratings; here it becomes stranded, owing to the diminished depth which accompanies the quicker flow, and thus gradually builds up a dam around the grating, outside which the subsequent drainage forms a sort of lake.

#### DUST AND MUD.

*Formation.*—The formation of dust and mud is due almost entirely to the destruction of the road-surface by iron tires and iron-shod horses; and to a large extent the tractive force required in such cases is a measure of the amount of destruction caused.

In 1907 a British Association Committee with which the Author was connected made a series of experiments on the tractive force required for wheels of various diameters and widths. The experiments were carried out by Professor Hele-Shaw with apparatus made from sketches which the Author supplied to the Committee; but the latter remembers stating at the time that the absolute values got in this way would be of little value unless the quality of the road was also investigated; and so it turned out.

The relative resistance of pneumatic and iron tires on roads has been stated as somewhere about 0·7, but the ratio of the destruction caused in each case is a very much smaller fraction, the greater part of the resistance to the pneumatic tires being accounted for by internal work done on tire-material and on the mud or dust at the road-surface. The only chance which the pneumatic tires have of breaking the surface is while turning, or when the speed is sufficient to make the wheels jump. Here the long area of contact is disadvantageous, as it involves transverse sliding between the road and the tire.

When the pneumatic tires are armed with steel studs, no doubt a certain amount of grinding will take place, though much less than with hard tires; but if there were no mud the necessity for such devices to prevent side-slips would not exist. It is the Author's opinion that if iron tires and iron shoes for horses were abolished, the formation of dust and mud would practically cease.



*Dust-Diffusion.*—With the low speeds attained by horse-traffic, the narrow wheels with which the carts and carriages are fitted have little effect in disturbing the dust, and what dust is raised is due chiefly to the action of the horses' hoofs. With motor-traffic on pneumatic tires, however, the case is very different. The Royal Automobile Club have for some years past taken great interest in the dust question, and rightly so, for the nuisance caused by dust has been responsible more than anything else for the feeling which, to some extent, exists against motor-cars in the mind of the public.

Careful experiments made by a Committee of the Club showed that the dust raised by motors is due to the action of the wheels only (at any rate at speeds below 30 miles per hour), but that this dust raised by the wheels becomes involved in the violent eddies left in the air by the body of the car, and is thus diffused in a cloud which is often many feet higher than the car itself. The shape of the body of a car and the clearance between it and the ground have considerable effect on the magnitude of the dust-cloud, and of course it is important that manufacturers should avail themselves of the knowledge which will enable them to reduce the dust-cloud to a minimum; but the Author considers that, judging from what he has seen, even four wheels with pneumatic tires but without any car-body would raise an objectionable quantity of dust on certain classes of road.

The question how dust is raised, whether by wheels, or by wind, is rather a difficult one. It would seem impossible that a uniform wind, free from eddies, should cause anything but a surface-drift of dust lying on the ground, for the flow of such a wind at the ground must be parallel to the surface. The actual motion of the air, however, near the surface is full of eddies due to surface friction (with their axes for the most part horizontal), so that there will be alternate upward and downward components in the current of air, and it is probable that dust disturbed laterally and deflected upwards by striking against neighbouring particles becomes involved in the ascending currents.

Observation shows that the small dust-squalls commonly seen on dusty roads during windy days are the result of a local downflow of air, the chief dust-disturbances taking place at the boundaries where the eddies are most violent.

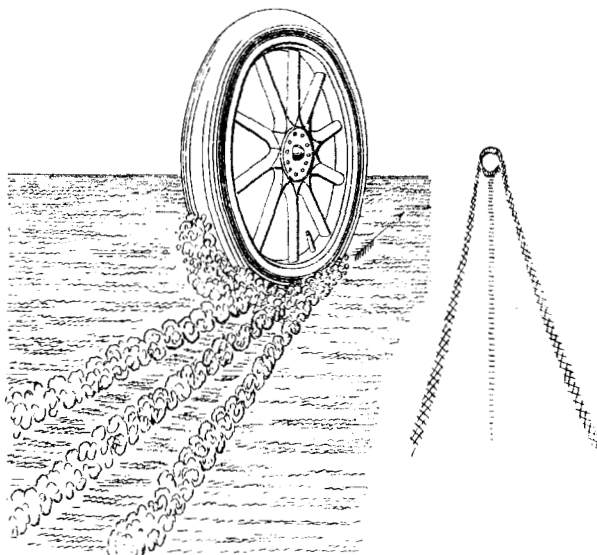
The form of disturbance caused in the dust by a ring-shaped tire consists of two broad waves spreading obliquely from either side of the front margin of contact with the ground (analogous to the bow waves of a ship), and in the rear it consists of a thin wall of dust,

which frequently reaches a height of 18 inches or more, and follows the wheel in the central plane (*Figs. 5*).

It is doubtful at present which of these sources contributes most to the general dust-cloud of the wake, and also in what proportion the bow waves are increased by the downflow of air brought about by the surface friction of the advancing front of the tire. The stream-lines of air round such a tire would be worth experimental investigation.

It is plain, however, that whatever the actual stream-lines may be, the lateral velocity, *ceteris paribus*, given to the air must be

*Figs. 5.*



proportional to the linear dimensions, and there can be little doubt that the dust-disturbance due to a current of air will vary as the square of its speed. It may be expected therefore that the dust raised by a tire will vary as the square of the diameter of the outer tube and as the square of the velocity, though much of the dust so raised falls quickly without being caught by ascending air-currents.

It was stated at the beginning of this Paper that the conditions required, for roads suited to elastic tires and mechanical traction, were in some respects less exacting than for horse-drawn traffic and hard tires. So far as the foundations of a road are concerned the

conditions are the same for both, and depend not on the nature of the vehicle but on the magnitude of the loads; as regards the surface, however, a very hard material is indispensable where iron tires are in use, but this is not nearly so important when the wheels are fitted with either pneumatic or solid rubber tires. Small roughnesses of surface, also, which would add considerably to the resistance of hard tires, are matters of no importance when the area of contact is large and the pressure is practically independent of the form of the surface pressed on. Irregularities of surface begin to tell in this case when their pitch is long enough to cause the wheels to leave the ground; and this in turn depends on the speed (at 20 miles per hour the length would be of the order of 3 feet).

If the whole of the facts are carefully examined, the Author thinks the unavoidable conclusion is that the real enemies to good roads are iron tires and iron-shod horses. It cannot be expected that these will cease to be used for many years to come (probably they will be always employed for some forms of slow traffic), but as they become fewer so will the general condition of the roads improve. In the meantime the wear can be minimized, so far as country roads are concerned, by the use of such plastic binding material as tar-compounds properly applied to the surface.

For town roads and streets much might be done towards freeing them from dust and dirt by the use of the hollow section and central drain suggested in *Fig. 4 (c)*. There are of course many practical difficulties in the way of applying this form to existing roads, with their numerous underlying pipes and cable-ways, but it would be well worth a trial should an opportunity occur.

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