HIGHWAY CONSTRUCTION. PART I: INSTRUCTION PAPER; PP. 1-111

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HIGHWAY CONSTRUCTION

PART I

INSTRUCTION PAPER

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HIGHWAY CONSTRUCTION

PART I

COUNTRY ROADS AND BOULEVARDS

RESISTANCE TO MOVEMENT OF VEHICLES

The object of a road is to provide a way for the transportation of persons and goods from one place to another with the least expenditure of power and expense. The facility with which this traffic or transportation may be conducted over any given road depends upon the resistance offered to the movement of vehicles. This resistance is composed of: (1) resistance offered by the roadway, which consists of (a) "friction" between the surface of the road and the wheel tires, (b) resistance offered to the rolling of the wheels occasioned by the want of uniformity in the road surface or lack of strength to resist the penetrating efforts of loaded wheels, (c) resistance due to gravity called "grade resistance"; (2) resistance offered by vehicles, termed "axle friction"; and (3) resistance of the air. The magnitude of each of the components has a wide range, varying with the kind and condition of the road and its surface, the form and condition of the vehicle, the load, and the speed.

Resistance to Traction. The combination of road resistances is designated by the general term "resistance to traction", the magnitude of which is measured by the number of pounds of effort per ton of the load required to overcome it; this is ascertained by a form of spring-balance variously called "dynograph", "tractograph", etc., one end of which is attached to the vehicles and the other end to the draft animals.

The road which offers the least resistance to traffic should combine a surface on which the friction of the wheels is reduced to the least possible amount, while possessing sufficient roughness to afford good foothold for the draft animals and good adhesion for motor vehicles; and should be so located as to give the most direct route with the least gradients.

TABLE I

Resistance to Traction on Different Road Surfaces

Road Surface	Traction Resistance	
	Pounds per Ton	In Terms of Load
Earth road—ordinary condition	50 to 200	$\frac{1}{40}$ to $\frac{1}{10}$
Gravel	50 to 100	$\frac{1}{40}$ to $\frac{1}{20}$
Sand	100 to 200	$\frac{1}{20}$ to $\frac{1}{10}$
Macadam	30 to 100	$\frac{1}{67}$ to $\frac{1}{20}$
Plank road	30 to 50	$\frac{1}{67}$ to $\frac{1}{40}$
Steel wheelway	15 to 40	$\frac{1}{133}$ to $\frac{1}{50}$

Friction. The resistance of friction arises from the rubbing of the wheel tires against the surface of the road; its amount can be determined only by experiment for each kind of road surface. From many experiments the following deductions are drawn:

(1) The resistance to traction is directly proportional to the pressure.

(2) On solid unyielding surfaces, the resistance is independent of the width of the tire; but on compressible surfaces it decreases as the width of the tire increases. There is no material advantage gained, however, in making a tire more than 4 inches wide, for the reason that it is impossible to distribute the load evenly over the road owing to the irregularities and curvatures of its surface.

(3) On uniformly smooth surfaces, the resistance is independent of the speed.

(4) On rough irregular surfaces, which give rise to constant concussion, the resistance increases with the speed.

Table I shows the relative resistance to traction of various surfaces. These coefficients refer to the power required to keep the load in motion. It requires from two to six or eight times as much force to start a load as it does to keep it in motion at two or three miles per hour. The extra force required to start a load is due in part to the fact that during the stop the wheel may settle into the road surface; in part to the fact that the axle friction at starting is greater than after motion has begun; and in part to the fact that energy is consumed in accelerating the load.

Resistance to Rolling. Resistance to rolling is caused partly by the wheel penetrating or sinking below the surface of the road, forming a depression or rut, as shown in Fig. 1, thus compelling the wheel to be continually rolling up a short incline. The measure of this resistance is the horizontal force necessary at the axle to roll it up the incline; and is equal to the product of the load multiplied by one-third of the semi-chord of the submerged arc of the wheel.

Resistance to rolling is also caused by the wheel striking or colliding with loose or projecting stones, which suddenly checks

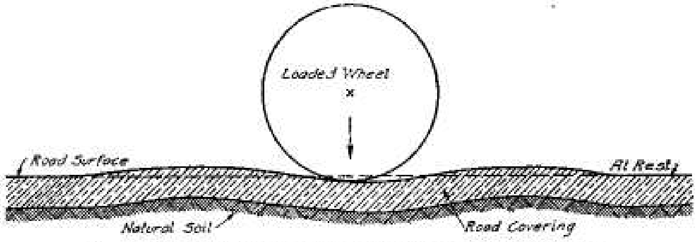

Fig. 1. Exaggerated Section of Road under Pressure of Loaded Vehicle

the motive power; the momentum thus destroyed varies with the height of the stone or obstacle and is often considerable.

In both cases the power required to overcome the resistance is affected largely by the diameter of the wheel, as the larger the wheel the less force is required to lift it over the obstruction or to roll it up the inclination due to the indentation of the surface.

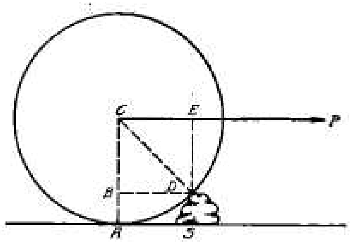

Fig. 2. Diagram for Calculating Power Required to Draw Wheel over Resisting Object

Illustrative Example. The power required to draw a wheel over a stone or any obstacle, such as S in Fig. 2, may be thus calculated:

Let P represent the power sought, or that which would just balance the weight on the point of the stone, and the slightest increase of which would draw it over. This power acts in the direction CP with the leverage of BC or DE. The force of gravity W resists in the direction CB with the leverage BD. The equation of equilibrium will be $P \times CB = W \times BD$, whence

$$P = W\frac{BD}{CB} = W\frac{\sqrt{CD^2 - BC^2}}{CA - AB}$$

Let the radius of the wheel equal $CD=26$ inches, and the height of the obstacle equal $AB=4$ inches. Let the weight $W=500$ pounds, of which 200 pounds may be the weight of the wheel and 300 pounds the load on the axle. The formula then becomes

$$P=500\frac{\sqrt{676-484}}{26-4}=500\ \frac{13.85}{22}=314.7 \text{ lb.}$$

The pressure at the point D is compounded of the weight and the power, and equals

$$W\frac{CD}{CB}=500\times\frac{26}{22}=591 \text{ lb.}$$

Therefore this pressure acts with this great effect to destroy the road in its collision with the stone; in addition there is to be considered the effect of the blow given by the wheel in descending from it. For minute accuracy the non-horizontal direction of the draft and the thickness of the axle should be taken into account. The power required is lessened by proper springs to vehicles, by enlarged wheels, and by making the line of draft ascending.

Illustrative Example. The mechanical advantage of the wheel in surmounting an obstacle may be computed from the principle of the lever. Let the wheel, Fig. 3, touch the horizontal line of traction in the point A and meet a protuberance BD. Suppose the line of draft CP to be parallel to AB. Join CD and draw the perpendiculars DE and DF. We may suppose the power to be applied at E and the weight at F, and the action is then the same as the bent lever EDF turning round the fulcrum at D. Hence $P : W :: FD : DE$. But $FD : DE :: \tan FCD : 1$; and $\tan FCD = \tan 2\, DAB$; therefore $P = W \tan 2\, DAB$. Now it is obvious that the angle DAB increases as the radius of the circle diminishes; therefore, the weight W being constant, the power required to overcome an obstacle of given height is diminished when the diameter is increased. Large wheels are, therefore, the best adapted for surmounting inequalities of the road.

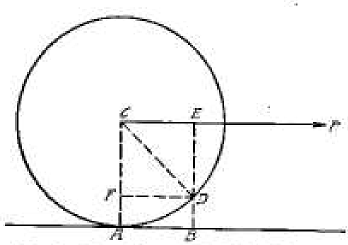

Fig. 3. Force Diagram for Wheel Drawn over Obstacle

TABLE II

Resistance Due to Gravity on Different Inclinations

Grade 1 inch	20	30	40	50	60	70	80	90	100	200	300	400
Rise in feet per mile	264	176	132	105	88	75	66	58	52	26	17	13
Resistance in pounds per ton	100	$66\frac{2}{3}$	50	40	$33\frac{1}{3}$	$28\frac{4}{7}$	25	$22\frac{2}{9}$	20	10	$6\frac{2}{3}$	5

There are, however, circumstances which provide limits to the height of the wheels of vehicles. If the radius AC exceeds the height of that part of the horse to which the traces are attached, the line of traction CP will be inclined to the horse, and part of the power will be exerted in pressing the wheel against the ground. The best average size of wheels is considered to be about 6 feet in diameter. Wheels of large diameter do less damage to a road than small ones, and cause less draft for the horses. With the same load, a two-wheeled cart does far more damage than one with four wheels, and this because of their sudden and irregular twisting motion in the trackway.

Grade Resistance. Grade resistance is due to the action of gravity, and is the same on good and bad roads. On level roads its effect is immaterial, as it acts in a direction perpendicular to the plane of the horizon and neither accelerates nor retards motion. On inclined roads it offers considerable resistance, proportional to the steepness of the incline. The resistance due to gravity on any incline in pounds per ton is equal to

$$\frac{2000}{\text{rate of grade}}$$

Table II shows the resistance due to gravity on different grades. The additional resistance caused by inclines may be investigated in the following illustrated example.

Illustrative Example. Suppose the whole weight to be borne on one pair of wheels, and that the tractive force is applied in a direction parallel to the surface of the road.

Let AB, Fig. 4, represent a portion of the inclined road, C being a vehicle just sustained in its position by a force acting in the direction CD. It is evident that the vehicle is kept in its position by three forces: namely, by its own weight W acting in the vertical direction CF; by the force F applied in the direction CD parallel