While 1930 was especially annoying to the motorist because practically every main highway in the region of Chicago was barricaded at one point or another for widening or other improvement, it appears that most of the main arteries into and around the city will be usable during 1931, or will have a satisfactory parallel nearby.

TRAFFIC CAPACITY OF HIGHWAYS

By Nathan W. Dougherty, Professor of Civil Engineering, University of Tennessee

The traffic capacity of a highway depends upon at least three things: the width of the vehicle, the speed of the vehicle, and the uniformity of speeds. Other factors enter in, such as curvature and local surroundings, but these three are primary.

The over-all dimensions of the vehicle determine the width of the traffic lane. If a highway is to carry a large amount of truck or motor bus traffic, the width of each lane must be sufficient to allow easy passage of wide-bodied vehicles in addition to a clearance at the edges of the pavement and a clearance between the vehicles themselves. The ability to overtake and pass a more slowly moving vehicle is largely determined by the width of the traffic lane, and, of course, by the width of the vehicles passing.

When the lane is narrow, speeds are limited for ease of control. As the speed is increased, the width of the lane must be increased up to a practical minimum value, other things being equal, depending upon the speeds at which vehicles travel. Vehicles moving at very low speeds are under excellent control and the driver has no fear of leaving the roadway or taking the ditch and can, therefore, drive near the edge of the pavement. As the speed increases, a small change in direction carries the vehicle very rapidly into the ditch or into the opposing lane. To make the driver feel safe and actually to furnish him with more safety, the width of the lane must be increased.

It is obvious that the number of lanes is dependent upon the relative speed of the vehicles. If a certain number of the vehicles move at 15 miles an hour and another number at 30 miles an hour, the more slowly moving vehicles must be overtaken by those moving with the faster speed. To overtake and pass a vehicle, an extra lane is needed on the highway. The lane ordinarily used by traffic moving in the opposite direction can be utilized, provided the traffic in the opposite direction is not sufficient to obstruct the movement.

But there is a point at which it is practically impossible to use the opposing lane. Then all vehicles must fall in line and move at the slowest speed in the lane.

Theoretical Capacity

A number of equations have been developed giving the theoretical capacity of a traffic lane. Some of them have been based upon experimental data and some upon purely theoretical considerations. We will present an equation which seems reasonable and which by varying the factors can be made to suit theoretical conditions. A number of assumptions must be made.

To treat the problem theoretically, the movement must follow some uniform law. We, therefore, assume that the speeds are uniform, that the space between vehicles is safe, and that the flow is continuous. Our problem, then, is to determine a safe space between vehicles.

Dean Johnson observed on the Washington-Baltimore Highway that vehicles space themselves approximately as the square of the speed. This is theoretically as it should be. If we equate the kinetic energy in the moving vehicle to the work of friction required to bring the vehicle to a stop, we will find that the distance is dependent upon the square of the velocity. Our equation will read as follows:

$$f\,w\,d = \frac{w\,v^2}{2\,g}$$

The left hand side of the equation is the work of friction where f is the coefficient of friction, w the weight of the vehicle, and d the distance required to stop. On the right hand side of the equation, w is again the weight of the vehicle, v is the velocity in feet per second, and g is the acceleration of gravity. If we assume the coefficient of friction to be 0.6, we arrive at the following equation for distance:

$$d = \frac{v^2}{1.2\,g}$$

More distance is needed than that given by the above equation. There must be a clearance from front of vehicle to rear of vehicle and an additional distance to allow a driver to take his foot from the throttle and place it on the brake. When a driver observes disaster ahead, it requires a certain amount of time between the observation and the application of brakes. Observations have been made of the required time for many drivers, and it has been found to vary from 2/10 of a second to 1½ seconds. If the reaction time is as much as 1½ seconds, the driver, unless he is exceedingly cautious, will probably arrive at disaster before he can possibly stop the vehicle.

When we realize that 40 miles per hour is equivalent to a speed of 59 feet per second, we see that a vehicle will move 88 feet in 1½ seconds. The stopping distance for 40 miles per hour with the use of four-wheel brakes is approximately 90 feet. If we assume 5/10 of a second as an average reaction time, we develop the following equation for capacity of the highway.

$$N = \frac{3600\ v}{15+0.026\ v^2 + 0.5\ v} \text{ or } N = \frac{5280\ V}{15 + 0.056\ V^2 + 0.73\ V}$$

where V is velocity in miles per hour.

Notice that the capacity varies as the square of the speed, increasing with low speeds up to 16 miles per hour and decreasing with higher speeds. This means that there is a critical speed at which there is a maximum flow, and substitution in the equation gives this flow to be approximately 2,100 vehicles per hour.

Dean Johnson's observations on the road gave him an equation of

$$N = \frac{5280\ V}{0.5\ V^{1.3} + 15}$$

or varying as the square of V, he writes

$$N = \frac{5280\ V}{\frac{V^2}{15} + 15}$$

The first equation gives a maximum capacity of 2,800 vehicles per hour and the second equation gives a capacity of 2,600 vehicles per hour.

Mr. Johannesson has just published a little book on highway economics in which he devotes a short chapter to density of traffic and another to capacity of highway. His method is somewhat different from the two methods just described. He assumes that vehicles should be spaced at least 1½ seconds apart, plus an over-all length and standing clearance of 25 feet. When translated into the symbols given above,

$$N = \frac{5280\ V}{2.2\ V + 25}$$

which for 30 miles per hour gives 1,740 vehicles per hour, a value probably more in keeping with the actual maximum traffic to be expected upon the road.

A similar equation was presented to the Traffic Committee by Mr. Van Duzer of the Pennsylvania Highway Department during the summer of 1927. His stopping time was made to vary with the speed of the vehicle, thus changing the results slightly from those obtained by Mr. Johannesson.

Effect of Differences in Speeds

Not all vehicles move at a speed of 16 miles per hour when the maximum flow occurs. When vehicles move at different speeds, a passing lane must be provided. If the highway is a two-lane highway, the lane for the opposing traffic must be reasonably free to allow the faster vehicles to overtake those moving more slowly. It requires a minimum of 400 feet to allow a vehicle moving at 30 miles per hour to overtake and pass a vehicle moving at 15 miles per hour. This means that the on-coming lane must be free for at least 400 feet. If the fast moving vehicle must overtake a second slowly moving vehicle as soon as the first has been successfully passed, it means that the on-coming lane must be practically free. Mixed traffic, therefore, tends to reduce the capacity of a two-lane highway, and under practical conditions probably reduces it to approximately the capacity of one lane. Assumption as to speed and spacing can be made and a theoretical equation developed. Such an equation, however, is of very little practical value, since the vehicles will not use the desired speeds.

We immediately ask whether there has been a comparison of the theoretical capacity with the actual highway conditions. We have made observations in Tennessee and find that vehicles can move at a capacity of 1,000 vehicles per lane in both directions without a large amount of congestion.

Observations outside of Tennessee with more dense traffic as in the Holland Tunnel show 1,900 vehicles per hour per lane. This approaches the maximum capacity.

Under ideal conditions with uniform speed, the practical capacity approaches the capacity given in the above equations. This is witnessed by the Holland Tunnel. On the open highway, however, vehicles will move at varying speeds and be of different characters, therefore greatly modifying the theoretical conditions. We will attempt to estimate the capacity of the several widths of highway. Before doing so, we should undertake to define the limit of capacity or traffic congestion. My own definition is hindrance of free movement of vehicles over a highway or street because of other similarly moving vehicles. Dean Johnson of the University of Maryland has made an extensive study of traffic movement, and he defines traffic congestion as follows: "There will be reached a point at which some vehicles will be delayed because they are immediately unable to pass other slower moving vehicles." It is obvious that congestion will come at the peak period while there will be no congestion during other hours of the day. The daily capacity of the highway will, therefore, be different from the maximum capacity without traffic interference. The maximum hour is usually 60 to 90 per cent higher than the average flow during the day from 7 a. m. to 7 p. m.

Capacity of One-Lane Road

The usual criterion for the capacity of the one-lane road with shoulders for passing is placed at some number of passings per mile. Some observers state that the capacity is reached when vehicles must meet other vehicles at least three times per mile. If the vehicles are coming in opposite directions and three passings per mile are placed as the maximum, and the speed be assumed at thirty miles per hour, the capacity of the one-lane highway will be 90 vehicles per hour for both directions. Assuming 90 vehicles per hour as a maximum hour, the average will be reduced to 50 vehicles per hour or 500 vehicles per 10-hour day. My own personal belief is that a single lane highway which is carrying 500 vehicles per 10-hour day is overloaded and that the traffic demands a two-lane surface.

Capacity of Two-Lane Highway

A two-lane highway allows movement in both directions and overtaking when the opposing lane is free. If the vehicles are moving at a uniform speed, the capacity will approximate 4,000 vehicles per hour. At this rate, the capacity of the two-lane road for a 10-hour day will be 40,000 vehicles, which is more than the practical capacity of an actual highway. Fortunately, the maximum flow on most highways comes on a holiday or Sunday when most of the vehicles are moving at approximately the same speed. This allows the practical capacity to be higher than it would be if the maximum demand came with mixed travel.

Observations on two-lane highways in Tennessee indicate a congestion somewhere between 1,000 and 1,400 vehicles per hour or at an approximate daily capacity of 6,000 to 7,000 vehicles per 10-hour day.

Dean Johnson presented to the Highway Research Board at its meeting in Washington his observations for the summer, and he notes that there is no serious amount of congestion on a two-lane road when the traffic is moving at a rate of 1,000 vehicles per hour. He further notes that congestion begins around 1,300 vehicles per hour. His results are in conformity with the observations in Tennessee and are based on much more extensive data. Our conclusion is that a two-lane highway can carry from 6,000 to 10,000 vehicles per day, depending upon the distribution by direction and the uniformity of speeds.

Capacity of Three-Lane Highway

For many years we have debated the value of the three-lane highway. The third lane is not covered by the present rules of the road and, as a consequence, there has been a fear that three lanes will introduce an extra highway hazard. When we analyze this fear, we see that the danger is no greater than that afforded by the two-lane road. It is true that the onus for an accident is placed on the driver occupying the wrong lane when the accident occurs on the two-lane road, but few drivers are seeking danger. They are just as apt to turn back into the traffic when two vehicles turn into the passing lane as they are if driving on the two-lane road. Personal safety of the individual requires it, the only difference being, of course, that each driver may expect the other to give right-of-way and that an accident may follow.

Our experience in Tennessee is that the three-lane road satisfies a need intermediate between two and four lanes. The traffic uses the two outside lanes for normal flow and the third lane for passing more slowly moving vehicles. Oil drippings on the pavement show that the two outside lanes are used much more than the third lane.

We have observed vehicles moving at the rate of 1,400 vehicles per hour with no apparent congestion. The three-lane road under observation leads into a road of four lanes at one end and two lanes at the other. At the two-lane end, there was congestion when the rate reached 1,400 vehicles per hour and the tendency was for the vehicles to form in line and all use the same speed. At the four-lane end, during our period of observation, there was a tendency to move into the middle lanes, thus reducing the capacity of the highway. This habit, however, can be changed by proper signs and proper education by traffic officers. Our experience in Tennessee does not indicate the capacity of the three-lane highway. Fortunately, we have information from Dean Johnson's studies, which show there is little congestion up to 1,500 vehicles per hour, with congestion beginning between 1,600 and 1,900 vehicles per hour. This means that the traffic capacity of a three-lane road is approximately 50 per cent above the capacity of the two-lane road.

Heretofore we have been willing to admit that the three-lane road was useful when a preponderance of the travel was in one direction. It is certainly useful under such conditions. Dean Johnson's results show little congestion up to 2,300 vehicles per hour when 80 per cent of the traffic is in one direction.

All of the evidence available indicates that the three-lane road is not only useful for unbalanced travel but is very useful for the balanced travel. It is true that the third lane is not covered by the rules of the road; yet the evidence does not seem to indicate a more serious accident rate than on the two- or four-lane road.

Mr. Johannesson concludes that the three-lane road will practically double the capacity of a road with two lanes.

Capacity of the Four-Lane Highway

There is very little available information indicating the capacity of the four-lane highway. We know that it is much more than twice the capacity of the two-lanes. Reports from Connecticut indicate a flow of 40,000 vehicles per day on the Boston Post Road on certain peak days. Where two lanes are available in the same direction, the traffic can separate by speeds, allowing two lanes to flow at approximately their maximum capacity.

The information at hand indicates that a four-lane highway has a larger capacity than two two-lane roads separated by a parking space or parkway. To get the added capacity, one of the third lanes must be used to overtake vehicles moving in the direction of the preponderance of travel. Mr. Johannassen, in discussing the capacity of the four-lane road, says: "A four-lane roadway is capable of carrying a volume of traffic of such magnitude as may be met with except in locations where the traffic is exceptionally great, providing the four traffic lanes are free to carry the traffic and are not blocked by parked vehicles or otherwise.

"More than four traffic lanes on a roadway is generally inadvisable, because when the number is greater than four and they are all occupied, the smoothness of operation is interfered with. Drivers become nervous and anxious and accidents are likely to occur. When more than four traffic lanes are needed to take care of the traffic, it may be better to build another highway at another location to serve the additional traffic. Of course, if it is desired to make room for parking vehicles, it is proper to build the roadway with additional width."

It is probable that four lanes will carry the maximum traffic demanded on highways except in the urban areas. When the capacity of four lanes is reached, a new location will prove to be a more economical design than the addition of lanes over and above a maximum of four.

SETTLING FILLS ON MUCK LANDS

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Muck pockets or peat marshes are important topographic features to be considered in the location and construction of highways. They are encountered quite frequently in the northern part of this state. To one who is not familiar with them, they may not seem objectionable or at all serious in road location and construction; but experience will teach one