The flow thus has certain general properties. The flow may be zero in two significant ways:

1. if there is no traffic ($\rho = 0$), or
2. if the traffic is not moving ($u = 0$ and thus $\rho = \rho_{max}$).

For other values of density ($0 < \rho < \rho_{max}$), the traffic flow must be positive. Thus, in general, the traffic flow's dependence on density is as illustrated in Fig. 63-2. This flow-density relationship is sometimes called the **Fundamental Diagram of Road Traffic**. This shows that a maximum of traffic flow occurs at some density (with a corresponding velocity). Traffic engineers call the maximum traffic flow the **capacity** of the road. We *assume* that the flow-density relationship is as sketched in Fig. 63-2, concave downwards, $(d^2q/d\rho^2) < 0$. In other words we *assume* that $dq/d\rho$ decreases as ρ increases, as demonstrated in Fig. 63-3. The absolute maximum of the flow occurs at the only local maximum.

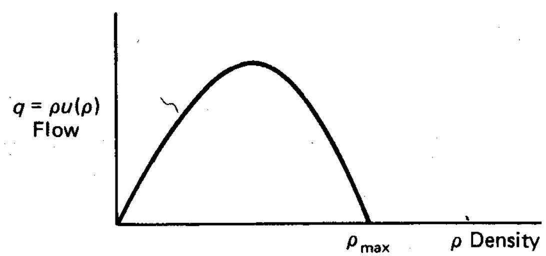

Figure 63-2 Fundamental Diagram of Road Traffic (flow-density curve).

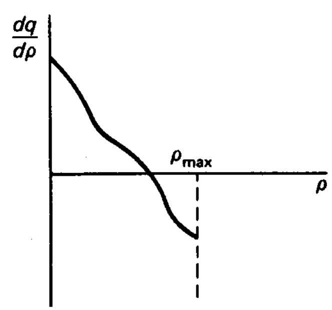

Figure 63-3.

The data from the Lincoln Tunnel indicate a maximum traffic flow of about 1600 vehicles per hour, occuring at a density of about 82 cars per mile, moving at a velocity of about 19 miles per hour. The data from the Merritt Parkway, Fig. 63-4, is inconclusive as the velocity range in which the maximum occurs was not observed.

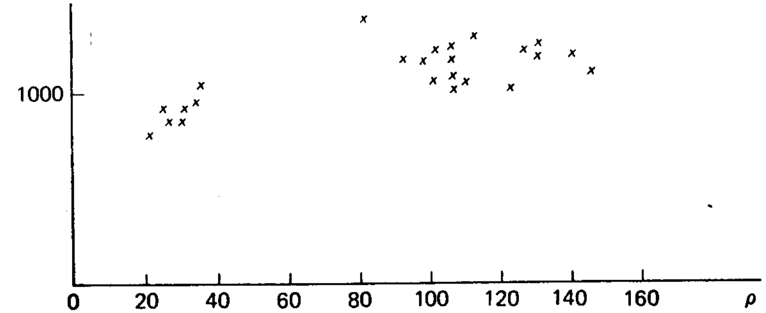

Figure 63-4 Merritt Parkway flow-density data.

If the density is almost zero, then the traffic usually travels at the maximum speed, u_{max}. Even as the density is somewhat increased, the cars' velocity remains nearly u_{max}. Thus for small densities the flow q can be approximated by $u_{max}\rho$, increasing linearly with the density. Measurements in the Lincoln Tunnel and in the Holland and Queens-Midtown Tunnels (other tunnels into New York City) show nearly identical linear flow-density relationships for small traffic densities, as was suggested by the previous theoretical discussion. However, as the density increases and the flow correspondingly increases, differences among the three tunnels develop in the flow-density curves. These measurements have shown that the maximum traffic flow (the capacity) and the corresponding velocity are both lower in the older tunnels. This indicates that the newer tunnels, with greater lane width, improved lighting, and so on, permit drivers to go faster at the same traffic density.

In addition, flow-density measurements have been made in different segments of the same tunnel. These experiments have shown that the capacity of the roadway varies. There are places in which the capacity is lower than elsewhere, what might be called bottlenecks. Typically in tunnels these bottlenecks occur on the upgrade of the tunnel. Can you suggest why they occur there?

To improve traffic efficiency, traffic should somehow be forced to move at a density (and speed) corresponding to maximum traffic flow. To illustrate an application of this concept, consider a situation in which many cars are waiting to enter a tunnel. Assume that the cars, as often occurs, are moving at a speed less than that associated with maximum flow (i.e., more cars per mile than is most efficient!). A signal which literally stops traffic and then permits it to go (in intervals yielding the density corresponding to maximum flow) would result in an increased flow of cars through that tunnel. Thus, momentarily stopping traffic would actually result in an increased flow! Although we have simplified the problem somewhat, this idea resulted in increased traffic performance in the Holland Tunnel as reported in Scientific American.*

*HERMAN, R. and GARDELS, K., "Vehicular Traffic Flow," *Scientific American 209 No. 6*, December 1963, pp. 35–43.