Case Study
Capacity of a Highway Intersection

This case study explores the capacity of a highway intersection in order to illustrate the differences among maximum capacity, operating capacity and sustainable capacity.

Consider a typical intersection of two arterial streets in an urban area, one of which carries eastbound and westbound traffic, while the other street carries northbound and southbound traffic. To simplify the situation, assume that a) all of the vehicles are automobiles, b) none of the vehicles are making any turns, and c) there are no pedestrians. The traffic signal has a cycle time of 120 seconds, and it provides equal time (60 seconds each) for the east/west and the north/south flows. When the signal turns green, it takes 2 seconds for the first car to move through the intersection; if there is a queue of cars, then additional cars can pass through every 2 seconds. Thus, the maximum number of cars in one lane that can move through the intersection in each two-minute cycle is:

(60 seconds green/cycle)/(2 seconds/car) = 30 cars/cycle

If both roads are two-lane roads, then there would be a total of 4 lanes that approach the intersection and there could be as many as 4 lanes multiplied by 30 vehicles per lane or 120 vehicles moving through the intersection during each two-minute cycle, and there could on average be one vehicle per second moving through the intersection.

Is the capacity of this intersection therefore one vehicle per second or 60 vehicles per minute? If so, is this the same as saying that the capacity is 60 vehicles per minute or 3600 vehicles per hour or 24 hours/day (3600 vehicles/hr) = 86,400 per day?

Given the assumptions, these may appear to be reasonable statements. However, we probably should be somewhat suspicious of the nice round numbers used in the above analysis. If you really want to know the capacity of the intersection, you could stand on the corner and count cars. If you had a stopwatch and a clipboard, you could record the actual number of cars moving through on each cycle and you perhaps would find that sometimes the first car takes 4-5 seconds (until the driver behind honks), while subsequent cars take a little more than two seconds. With better information about how cars move through the intersection you would be able to say something like this: the maximum number of cars passing through the intersection at rush hour during one week in October was 56; the average number of cars passing through the intersection was 52. Moreover, you noted that there was never enough time for all of the waiting cars to get through in one cycle, so that these observations were directly related to the capacity of the interchange. Armed with this knowledge, you might conclude that capacity was somewhat less than 60 cars per minute. And you might wonder whether the capacity should be stated as 60 (which is what was calculated using the textbook approach described above), 56 (the maximum that you yourself saw) or 52 (the average that you observed)?

Before answering this question, let's think about how this measure of capacity might be used. If we are traffic engineers or planners, we likely would be comparing the capacity of the intersection to the volume of traffic that is expected to be trying to get through the intersection; if capacity is insufficient, we would then be considering whether it is worthwhile to expand capacity or to reduce demand (e.g. by establishing tolls or by promoting the use of transit). If we are commuters, we are likely worried about excessive delays if there is insufficient capacity. Engineers, planners, and commuters would all be thinking about the extent of the delays, and they would all be concerned with what happens during the morning and afternoon rush hours. Thus, they would be thinking about cars per hour rather than cars/minute. While all might agree that the theoretical capacity is somewhere between 56 and 60, they would all prefer to use no more than the observed average of 52 in their comparison of capacity to demand.

Is there any reason to consider something less than 52 cars/minute as the estimate of capacity? Yes, indeed. Any experienced commuter would have some questions about the study that you completed:

- Were there any accidents during that week?
- What was the weather like (were there any heavy rains or snowstorms)?
- Were there any emergency vehicles trying to move through the intersection?
- Was there any maintenance in or near the intersection?
- Was the intersection ever gridlocked (i.e. did cars ever enter the intersection without being able to continue all the way through, thereby blocking the intersection when the light turned green for the other traffic)?

Commuters ask these questions because they know that accidents, bad weather, emergency vehicles, and aggressive drivers all disrupt normal flows, not necessarily every day but often enough to be a problem. A more extensive study that included winter conditions and periods of maintenance might show that the average flow through the intersection was actually only 48 cars per minute during rush hour.

So is the capacity of the interchange 48 cars per minute? Well, the commuters and the planners would ask another question: how bad are the delays at this intersection? It could be that this is a notorious intersection where cars back up for a half-mile or more and it often takes 10-15 minutes to get through. Anyone driving that route on a regular basis would say that such delays are unacceptable, and planners would likely agree that the intersection was experiencing traffic volumes that were higher than its capacity. This may seem to suggest that the capacity is less than 48 cars per minute, but actually it doesn't. The capacity of the intersection is in fact about 48 cars per minute, but traffic volumes during rush hour are greater than this; the long queues build up because cars arrive faster than cars can get through the intersection. When an incident happens, whether related to an accident or to a snow-storm or to anything else, fewer cars move through the intersection and queues build up to an unacceptable level.

A traffic engineer might then ask the following question: if the average throughput of the intersection is 48 cars/minute during rush hour, what is the maximum traffic volume for which the performance of the intersection is acceptable? This question could be phrased in terms of the structure of the street network: what is the maximum traffic volume for which the queues at this intersection will interfere with the performance of neighboring intersections no more than once or twice a month? This question could be answered using algebraic models or by simulating traffic conditions. If a delay of a few minutes is acceptable, then it will certainly be possible for more than 48 cars/minute to be arriving during rush hour even though only 48 cars/minute will get through the intersection.

The discussion thus far has only considered rush hour, and the estimates of capacity all related to what happens during rush hour. In designing systems, it is essential to consider capacity during the peak period, but estimates of demand may be phrased in terms of daily, weekly, monthly or annual usage. It is therefore necessary to be able to translate peak period capacity into capacity for these other periods. This can be done by considering the pattern of demand over longer periods. For highways, the following relationships can be estimated based upon observations of traffic volumes:

- Average vehicles per day on week days over an entire year
- % of traffic on weekdays
- % of traffic during peak periods of the day

For example, if the capacity of an intersection is 50 vehicles/minute during rush hour, then the capacity for the four peak hours will be 12,000 vehicles during four peak hours. If the rush hour periods account for 40% of weekday traffic, then the intersection can be considered to have capacity for 12,000/0.40 = 30,000 vehicles per weekday. If weekdays have 80% of the average weekly traffic, then the capacity is 30,000 vehicles per weekday x 5 weekdays/week / 0.80 = 187,500 vehicles per week or 9.375 million per year, assuming that the current traffic patterns remain the same. This statement can be interpreted as follows: if traffic along these two roads rises to 9.4 million per year, then this particular intersection is likely to experience unacceptable delays on a regular basis. The intersection might actually handle more traffic, but the delays would increase and the congested rush hour periods would be longer. In other words, this intersection is expected to act as a bottleneck once traffic along these two roads rises to 9.4 million vehicles per year.

The capacity of the network will be harder to define, because there will be many possible bottlenecks. There may be severe problems at other points in the network long before our intersection experiences significant delays. If it is easy to add capacity, then it may be possible to add capacity as demand grows, thereby avoiding the development of bottlenecks.

If there are many potential bottlenecks within the network, then fixing one of them will not necessarily affect system performance. Increasing the capacity of one intersection by building an overpass may simply shift the delays to the next intersection.

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