THE BENEFITS OF ACCOMMODATING LATENT DEMAND

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Abstract

Latent demand consists of trips not made at a particular time on a particular route because the cost of the trips is too high but which would be made if the cost were lower. If capacity on a congested freeway is increased, some of this latent demand will be accommodated. As a result, the reduction in peak period delay on the freeway will be less than would be projected if there were no latent demand, and there will be some increase in overall vehicle miles. Generally, only these negative aspects of latent demand are considered.

However, there are significant benefits from accommodating latent demand. The most important is the reduction in "schedule delay," that is leaving earlier than desired in order to reach one's destination on time, perhaps arriving earlier than desired. When capacity is increased, people can leave later and still arrive on time. Another important benefit is the reduction in delay on alternate routes as people shift from these routes to the highway. With such shifts the total delay reduction on all routes is greater than if there were no route shift. There may also be new trips that would not have been taken before the improvement because they took too long or preferred destinations not visited because they took too long.

A balanced assessment of the benefits and costs of increased capacity would include the positive, as well as the negative, effects of latent demand.

The Benefits of Accommodating Latent Demand

Introduction

Latent Demand Defined

The benefits of transportation improvements that reduce delay are often discounted because some of the delay reduction will be offset by latent demand. Latent demand consists of vehicle trips not made at a particular time at a particular location on a particular route because the cost of the trips is too high but which would be made if the cost were lower. When capacity is increased some of this latent demand is accommodated. It may have several components. Trips may be shifted to the improved facility from other routes because the improved route will now be faster for some travelers. People will be able to depart later and still arrive on time after the improvement, and those who previously traveled on the shoulders of the peak in order to avoid delay may shift their trips to the peak period. Trips previously made via transit, bicycle, or foot may be shifted to single-occupant vehicle. There may also be new trips that would not have been made before the improvement because they took too long. The shorter travel time to an area may lead to an increase in activities that may motivate more trips. Trips that were previously linked in order to avoid traversing the congested facility more than once may be unlinked. People who previously engaged in an activity in one location because a trip to their preferred location via the congested route took too long may shift their activity to the preferred location.

Generally only the negative aspects of latent demand are considered. It is often argued that improvements to highways are futile because any increase in capacity will be absorbed by latent demand, and congestion will remain. This argument ignores the fact that demand is not infinite; it *is* possible to increase capacity more than demand and thus reduce delay. This can be seen in Figure 1, which shows the demand, D, for travel on a particular freeway section at a particular time of day, and the supply, S, the ”price” in terms of travel time on that section of freeway. The supply curve is horizontal until capacity is reached at C, after which the travel time increases as each additional user imposes a delay on the other users. If capacity is increased to C’ the supply becomes S’. With no latent demand, that is if the demand curve were vertical at Q, then the demand curve would cross the new supply curve at Q, and travel time would be reduced to t’. However, demand for travel on a particular section of highway at a particular time is quite elastic because there are other routes, other times to travel, other modes, and other possible destinations for each person’s trip. Therefore, as a result of the latent demand, Q’-Q, demand still exceeds capacity and the travel time is reduced only to t’’. The fact that delay is not eliminated and that vehicle trips at this time and location increase is often considered a negative. But with the increased capacity, travel time is still less than before because each user imposes less delay on the other users than before. The only way that the travel time would not be reduced by an increase in capacity would be if the demand curve did not slope downward.

Vehicle hours, a key factor in the production of some emissions, are reduced, and because hours are reduced for a large number of vehicles, the resulting reduction in emissions may not be offset by the additional emissions caused by the new trips of a smaller number of vehicles.

Of course travel time can increase if the demand curve itself shifts. But here, latent demand is defined as demand that already exists but is not expressed because the time cost is too high. It does not include increased demand brought about by increased population or employment or other increased activity. The former represents movement along the existing demand curve as shown in Figure 1; the latter represents a shift in the demand curve itself from D to D', resulting in an increase in volume from Q to Q' as shown in Figure 2. Increased population, employment or other activity are often associated with increased transportation system capacity because property development causes both. But increased transportation system capacity does not *cause* increased activity, and limited transportation system capacity does not *prevent* increased activity. In fact, congestion has increased in many areas precisely because activity increased without a commensurate increase in transportation capacity. Of course, population and employment will tend to go where there is less congestion, other things being equal, but congestion is usually associated with agglomerations of economic and cultural activity that attract additional population and employment.

This paper deals only with latent demand of the type shown in Figure 1. This demand applies to a location on a particular facility at a particular time of day. The slope (elasticity) of this demand curve is determined not only by the demand for participation in activities that require travel, but also by the alternate routes, modes or activity sites available to travelers and the flexibility they have regarding the time of day during which they travel.

Income versus Substitution Effects

The demand curve incorporates both the substitution and income effects of a change in the travel time cost. When the cost is lowered, people will substitute travel on this route at this time for travel at other times, on other routes, or on other modes or they will substitute travel on this route for some other activity. The time saved by the reduced travel time on the route increases the time they have available. This increased time can be used to travel to a preferred, more distant destination; to make additional trips on this and other routes; or to spend more time on other activities.

Relevant Literature

Studies on induced demand by Fulton, Noland, Meszler, and Thomas in 2000 (1), Noland in 2001 (2), and Hansen and Huang in 1997 (3) use similar models and show a strong association between increases in highway capacity and vehicle-miles traveled. These studies control for the effects of population and income, but not employment. So to the extent that increased jobs are not reflected in increased income, their results include some induced demand. Noland finds that lane-miles tend to lead vehicle-miles traveled but notes that this does not necessarily indicate causation.

Cairns, Hass-Klau and Goodwin (4) studied examples of *reductions* in road space in Europe, North America, and Japan and found that in many, but not all, cases there were significant reductions in total traffic on the networks studied, showing that reduced capacity can reduce travel. In these cases the movement along the demand curve, as in Figure 1, was toward the left rather than the right.

Fujii, and Kitamura (5) used one-day activity diary data from the Kobe-Osaka area to estimate the effects of two proposed new freeways on travel behavior and found an increase in in-home time and a slight increase in home-based trips. Their findings suggest that most of the travel time saving is used for non-travel activities and only a small portion is used for additional travel.

A household travel behavior survey by Colman (6) found that the most common response to increased highway capacity was a change in departure time. This was also found in a survey of travelers using the section of I-880 that was reconstructed 10 years after it was destroyed by an earthquake (7). The most common response to the time saving resulting from the reconstruction was to depart at a different time, usually later (41%). Seven percent shifted from transit, and 3% made trips they would not have made before the reconstruction.

Purpose and Structure of this Paper

The purpose of this paper is to identify and examine the benefits of accommodating latent demand and to suggest strategies for estimating these benefits. A simple freeway model will be utilized in identifying and examining the benefits. The paper will examine the various sources of latent demand: shifts of trips from less congested times of day, shifts from other routes, shifts from other modes, shifts to other destinations, reductions in trip chaining, and new trips.

Benefits of Accommodating Latent Demand

Freeway Model

Consider a freeway segment as shown in Figure 3. There is a bottleneck at the downstream end and the neck is long and uniform, contains no entry or exit points, and extends upstream beyond the area subject to congestion. The queue builds up and dissipates during the peak period as shown in the lower section of Figure 3. Vehicles arrive at a constant rate until the time of the maximum queue and then arrive at a constant lower rate until the queue is dissipated. The congestion on the freeway can be represented by a queue as shown in Figure 4, which depends on the length of the congested period, the maximum delay (maximum travel time minus free flow travel time), the time at which the maximum delay occurs, and the freeway capacity. The congested period extends from 0 to t_E, with the maximum delay occurring at t_{MAX}. The cumulative number of vehicles attempting to pass through the freeway bottleneck at time t is A(t) and the number actually passing through is Ct, where C is the capacity of the bottleneck per unit time.

$$A(t) = \int_0^t a(x)dx \qquad (1)$$

In this case $a(x)=a_1$ when $t < t_{MAX}$ and $a(x)=a_2$ when $t > t_{MAX}$.

$$Ct_E = t_{MAX}a_1 + (t_E - t_{MAX})a_2 \qquad (2)$$

$$t_E = \frac{t_{MAX}(a_1 - a_2)}{(C - a_2)} \qquad (3)$$

The maximum delay = $\frac{a_1 t_{MAX}}{C} - t_{MAX} = \frac{(a_1 - C)t_{MAX}}{C}$ (4)

The maximum queue = $(a_1 - C)t_{MAX}$ (5)

The total delay = $(a_1 - C)t_{MAX} \cdot t_E = \frac{(a_1 - a_2)(a_1 - C){t_{MAX}}^2}{2(C - a_2)}$ (6)

This queue can be used to estimate the changes in vehicle-delay and emissions from adding capacity to the freeway.

This model assumes that all delay is caused by queueing and none by increasing flows until those flows reach capacity, so that capacity is constant regardless of speed. This is consistent with research by Hall and Hall (8), Banks (9), and Chin and May (10). This means that the speed flow curve is a horizontal line at free flow speed until capacity is approached, at which point it begins to turn into a vertical line indicating constant capacity regardless of speed.

Benefits from Shifts in Departure Times

If capacity is increased at a freeway location where there is a queue, those users whose trip starting time is determined by the time they wish to arrive at their destination will alter their departure time because they can now leave later and still arrive on time. Increased capacity allows a reduction in "schedule delay," that is leaving earlier than desired in order to arrive on time. The relationship between departure time and desired arrival time at the destination is not straightforward. Newell (11) theorized that an individual's choice of departure time depends on perceived costs of waiting in the queue and arriving at the ultimate destination either early or late. Mahmassani and Chang (12) took another approach, using Simon's concept of "satisficing," which holds that people will search for a satisfactory, rather than optimal, situation.

Although it may not be possible to determine a distribution of desired or "satisficing" departure times, it is possible to examine the upper and lower bounds for the shift in starting times. Figure 5 shows these bounds when capacity is added. Figure 5a shows the initial conditions. The total vehicle-delay is the area between the two curves. Figure 5b shows delay with no shift in trip starting time. Capacity has been increased from C to C', thus shortening the congested period and eliminating much of the delay on the freeway. Delay has been reduced to

$$(a_1 - C')t_{MAX} \cdot t_E = \frac{(a_1 - a_2)(a_1 - C'){t_{MAX}}^2}{2(C' - a_2)} \quad (7)$$

The reduction in delay is $\frac{{t_{MAX}}^2 (a_1 - a_2)^2 (C' - C)}{2(C - a_2)(C' - a_2)}$ (8)

Figure 5c shows what would happen if everyone just left later so that delay on the freeway remained the same. The additional time at the trip origin (sleeping in, perhaps) is equal to the space between the two arrival curves, A(t) and A'(t), in Figure 5c. Because the total number of vehicles and the maximum delay are the same as initially, the following relations hold.

$Ct_E = a_1 t_{MAX} + a_2(t_E - t_{MAX})$, and therefore $t_E = t_{MAX} \cdot \frac{(a_1 - a_2)}{(C - a_2)}$ (9)

$Ct_E = C'(t_E - t_0)$, and therefore $t_0 = t_E \cdot \frac{(C' - C)}{C'}$ (10)

Maximum delay = $\frac{a_1 t_{MAX}}{C} - t_{MAX} = \frac{a_1 t_{MAX}}{C'} + t_0 - t_{MAX}'$ (11)

Therefore, $t_{MAX}' = \frac{a_1 t_{MAX}}{C'} - \frac{a_1 t_{MAX}}{C} + t_{MAX} + t_0$ (12)

The additional time at the trip origin is

$$\frac{a_1 t_{MAX}(t_{MAX} - t_{MAX}' + t_0)}{2} + \frac{(Ct_E - a_1 t_{MAX})(t_{MAX}' - t_{MAX})}{2} = \frac{t_{MAX}^2 (a_1 - a_2)^2 (C' - C)C}{2(C - a_2)^2 C'} \quad (13)$$

The additional time spent at the trip origin is greater than the delay reduction because

$$\frac{t_{MAX}^2 (a_1 - a_2)^2 (C' - C)C}{2(C - a_2)^2 C'} - \frac{t_{MAX}^2 (a_1 - a_2)^2 (C' - C)}{2(C - a_2)(C' - a_2)} = \frac{t_{MAX}^2 (a_1 - a_2)^2 (C' - C)^2 a_2}{2(C - a_2)^2 (C' - a_2) C'} \quad (14)$$

and all terms are positive.

To get a sense of the magnitude of this difference, consider a situation where the peak period is 3 hours long, the initial capacity is 6,000 vehicles per hour, and the maximum delay is ½ hour and occurs half way through the peak period. The total number of vehicles desiring to arrive by the end of the period is 18,000. If the same arrival pattern were maintained after the capacity was increased to 8,000 vehicles per hour, delay would be reduced by 4,500 vehicle hours. However, if everyone desired to arrive at the end of the peak period and the same delay was maintained, the additional vehicle hours at the trip origin would be 6,750. The time gained at the trip origin if departure times shifted such that the level of freeway delay remained the same is greater than the time saved in freeway delay if there were no shift in departure times. Reality would lie somewhere between the two.

Benefits of Shifts from Other Routes

If people are using an alternate route to a freeway in order to avoid freeway congestion, reducing delay on the freeway will induce some of them to return to the freeway. As a result, freeway delay will be reduced less than without the shift, but overall delay on the alternate routes as well as the freeway will be reduced more than without the shift because the people on the alternate routes are also benefiting from the increased freeway capacity.

To see this, let a(t) be the sum of $a_h(t)$ and $a_a(t)$, the number of vehicles arriving at the freeway and the alternate route, respectively, at time t. Let C_h and C_a be the initial capacities on the freeway and alternate route and $C_{h,}$' be the new capacity on the freeway. According to Wardrop's principle, at equilibrium, travel time on both routes will be equal. If free flow travel time on both routes is assumed to be equal, delay for a vehicle arriving at the freeway or alternate route at time t initially is

$$w_f(t) = \frac{A_f(t) - C_f t}{C_f} = w_a = \frac{A_a(t) - C_a t}{C_a} = \frac{A_f(t) + A_a(t) - (C_f + C_a)t}{C_f + C_a} \quad (15)$$

where t is the time since arrivals exceeded capacity.

If there were no route shifts when capacity on the freeway was expanded to C_f' delay for a vehicle arriving at the freeway at time, t, would be reduced to $\frac{A_f(t) - C_f{}'t}{C_f{}'}$ (16)

a reduction of $\frac{A_f(t)(C_f{}' - C_f)}{C_f C_f{}'}$ (17)

in delay for each vehicle entering the freeway and a total delay reduction for all vehicles entering the freeway between time t and t+Δt of $a_f(t) \cdot (\Delta t) \cdot \frac{A_f(t)(C_f{}' - C_f)}{C_f C_f{}'}$ (18)

With route shifts the delay for a vehicle entering either route at time t is reduced to

$$\frac{A_f(t) + A_a(t) - (C_f{}' + C_a)t}{C_f{}' + C_a} \quad (19)$$

a reduction of $\frac{(A_f(t) + A_a(t))(C_f{}' - C_f)}{(C_f + C_a)(C_f{}' + C_a)}$. (20)

This is a smaller reduction for each vehicle entering the freeway. However, the total delay reduction for all vehicles entering both routes between time t and t+Δt is

$$((a_f(t) + a_a(t)) \cdot (\Delta t) \cdot \frac{(A_f(t) + A_a(t))(C_f{}' - C_f)}{(C_f + C_a)(C_f{}' + C_a)} \quad (21)$$

The difference in total delay with and without route shifts for vehicles arriving at both routes between time t and t+Δt is

$$\frac{a_f(t) A_f(t) C_a (C_f{}' - C_f)^2 (\Delta t)}{C_f{}^2 C_f{}'(C_f + C_a)} \quad (22)$$

Since this is greater than one, the total delay will be reduced more with a route shift than without a route shift.

The route shift and delay reduction on all routes can be estimated with a simulation model.

To get a sense of the magnitude of this difference, consider a 3-lane freeway with a capacity of 6000 vehicles per hour that is expanded to a 4-lane freeway with a capacity of 8000 vehicles per hour. Assume that the alternate route has a capacity of 4000 vehicles per hour and that $a_f(t)$ is 7000 vehicles per hour and $A_f(t)$, the number of vehicles arriving at the highway since the number of arrivals exceeded capacity is 12000. In this case, the reduction in delay if there were no shifts in routes would be 30 minutes for a vehicle arriving at the freeway at time t. The reduction in delay for all vehicles arriving in the minute following t would be 58 vehicle-hours. With shifts in routes the reduction in delay for a vehicle arriving at the freeway at time t would be only 20 minutes. But the reduction in all vehicles arriving at both routes in the minute following t would be 65 vehicle-hours, 12% more than with no shifts.

Benefits of Mode Shifts

Anyone shifting to the freeway from another mode will benefit, otherwise they would not make the shift. Such shifts will increase vehicle miles and perhaps congestion in other locations and, if from transit, will reduce transit revenues. But increasing capacity on most freeways will not induce many people to shift to an automobile from transit. Transit users usually do not have access to an automobile for their trip or their destination is a congested downtown area where parking is expensive and hard to find. Only on a freeway leading to a location that is served by convenient transit and has convenient, reasonably price parking is it likely that significant numbers of people will shift from transit to automobiles. An example might be suburban rail to an office park; bus passengers on the route would experience the same travel time saving as cars and would not be motivated to shift. Increased capacity will not motivate people to shift from a carpool to driving alone because the travel time differential between carpools and single occupant vehicles would not change. Bicycle travelers often do not have access to an automobile or are bicycling for enjoyment or health. They are not likely to be saving time by bicycling rather than using an automobile, so reducing automobile travel time is not likely to cause them to switch modes.

The benefits to the travelers who shift from transit will be offset by the emissions they produce and the revenue loss to the transit agency, so that the overall result may be negative. However, the percent of non-automobile travelers in a freeway corridor is generally very small. Even if a large percent of them switched to automobile travel, it would represent a small percent increase in automobile travel.

Benefits of Shifts in Destinations

If a highway is congested, travelers may be in the habit of shopping at a grocery store that does not require travel via that highway. If travel time via that highway is reduced, some of them may change to a grocery store reached by that highway, either because it is better or because it is now easier to get to. Such shifts may result in more or fewer vehicle miles, but they will increase the welfare of the people making the switch, either because they save time or go to a better store, or both. The number of such shifts depends on the reduction in travel time and the geographic distribution of activity sites.

Effects on Trip Chaining

If travel time on a route is reduced, will people be motivated to link fewer of their trips? Consider the situation shown in Figure 6 and suppose the "cost" of linking the trip with another trip is K. This "cost" might be having to engage in the activity on the way home from work rather than going home first and engaging in the activity later. The "cost" might be the time away from one's family at a critical time of day rather than a more convenient time of day. Let A be the origin and B the destination of the primary trip, with C the location of the activity engaged in as a result of the linked trip. The travel time between A and C is $t_1 + t_2$. The travel time to make the linked trip is $2t_3$. The total cost of the linked trip is

$$t_1 + t_2 + 2t_3 + K$$

which is less than the cost of making two trips, which is

$$t_1 + t_2 + 2t_2 + 2t_3$$

In this case $K < 2t_2$.

If the travel time between where the linked trip leaves the primary route and the destination is reduced to t_2' the trip will be unlinked only if

$K > 2t_2'$. Under what circumstances are both of these conditions likely to be true? Only when half the "cost" K falls in a narrow interval between the original travel time and the new travel time. The greater the difference in travel times, the greater the likelihood that both of these conditions will be true.

Any reduction in trip chaining will increase vehicle miles. By increasing the number of trips, it will also increase vehicle emissions because trip end emissions are greater than running emissions.

Benefits of Induced Trips

People do not make some trips because the cost of the making those trips is greater than their value. Therefore, if the travel time cost were reduced, some additional peak period trips would be made. To see the interplay between travel time and the number of vehicle trips, consider the demand and supply shown in Figure 1. Rather than representing the way in which the number of trips changes over the course of the peak period, this figure represents the way in which the number of trips at a particular time during the peak period might change over the course of days and weeks. This can be thought of as a third dimension, not a shift in time or space but in trip making, assuming that demand and supply of freeway space at a particular time of day is in a steady state from day to day as a result of people making their travel decisions based on the their experiences on previous days and assuming that they have perfect information about travel times at different times during the peak period.

In Figure 1 the supply curve, S, indicates the cost in time for vehicles entering the freeway at a particular time. Once capacity is reached, at C, the cost for all vehicles rises as each additional vehicle imposes delay on the others. D indicates the number of vehicles wanting to use the facility at this time given various travel time costs.

A common way of looking at benefits is consumer surplus, the benefits that consumers receive above what they are willing to pay. Travelers on the demand curve to the left of Q are willing to take the trip if the time cost is at D, but the cost is only t, so the initial consumer surplus is the area left of D above t. When capacity is increased to C' and supply to S', the reduced delay increases the benefits to existing travelers by the amount in the rectangle bordered by t, t" 0, and Q. The number of new trips is Q'-Q. The consumer surplus for these trips is represented by the triangle bordered by Q, t" and D. The benefit from induced trips is less than the benefit of travel time savings to the initial travelers.

Costs of Accommodating Latent Demand

There is no cost in terms of added VMT or emissions associated with travelers who substitute travel at one time for travel at another time nor who use their travel time saving to engage in another activity. Travelers who substitute one route for another will increase or decrease VMT depending on which route is shorter. To the extent that people shift from other modes, make longer trips, or make additional trips, VMT and its associated emissions will be increased. But as discussed above, these responses are likely to be less common than departure time and route shifts.

Conclusion

The failure to consider the benefits of latent demand can lead to a substantial understatement of the benefits of adding freeway capacity. The greatest source of understatement is likely to be from the failure to consider shifts in departure time. As noted earlier, this is the most common response to an increase in capacity. In a survey of travelers on the reconstructed section of the earthquake damaged I-880 freeway in Oakland 41% reported changing their departure time. The understatement is greater the greater the initial delay and the greater the increase in capacity.

Another important understatement of benefits arises from failure to consider route shifts. This is the second most common response to an increase in capacity. This understatement is greater the greater the capacity of alternate routes and the greater the increase in freeway capacity.

Substantial diversions of trips from transit would occur only on freeways on routes with good rail transit leading to areas where parking was available and reasonably priced. As noted earlier the diversion of trips from transit after the reconstruction of I-880 in the San Francisco Bay area was 7%, and this section of freeway is well served by rail transit and has much higher than average transit use. These benefits would likely be small and would be offset by reductions in transit revenues and an increase in overall traffic beyond the improved section of freeway.

The number of people who would benefit from traveling to preferred locations or unlinking linked trips as a result of the reduced travel time is difficult to assess. It would depend on the magnitude of the travel time saving and the geographic distribution of activities, but is likely to be far less than the benefit from shifts in departure times and routes.

The benefit of new trips is likely to be small because these trips have so little value they were not made when the travel time was longer. The I-880 survey found that only 3% percent of travelers would not have made the trip.

Taken all together the benefits of accommodating latent demand can be substantial, and the focus only on the negative effects only can result in underestimation of the overall benefits of increasing capacity.

Acknowledgements

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List of Figures

Figure 1 Latent Demand – Increased capacity, S’, reduces travel time to t’, increasing the number of vehicles to Q’.

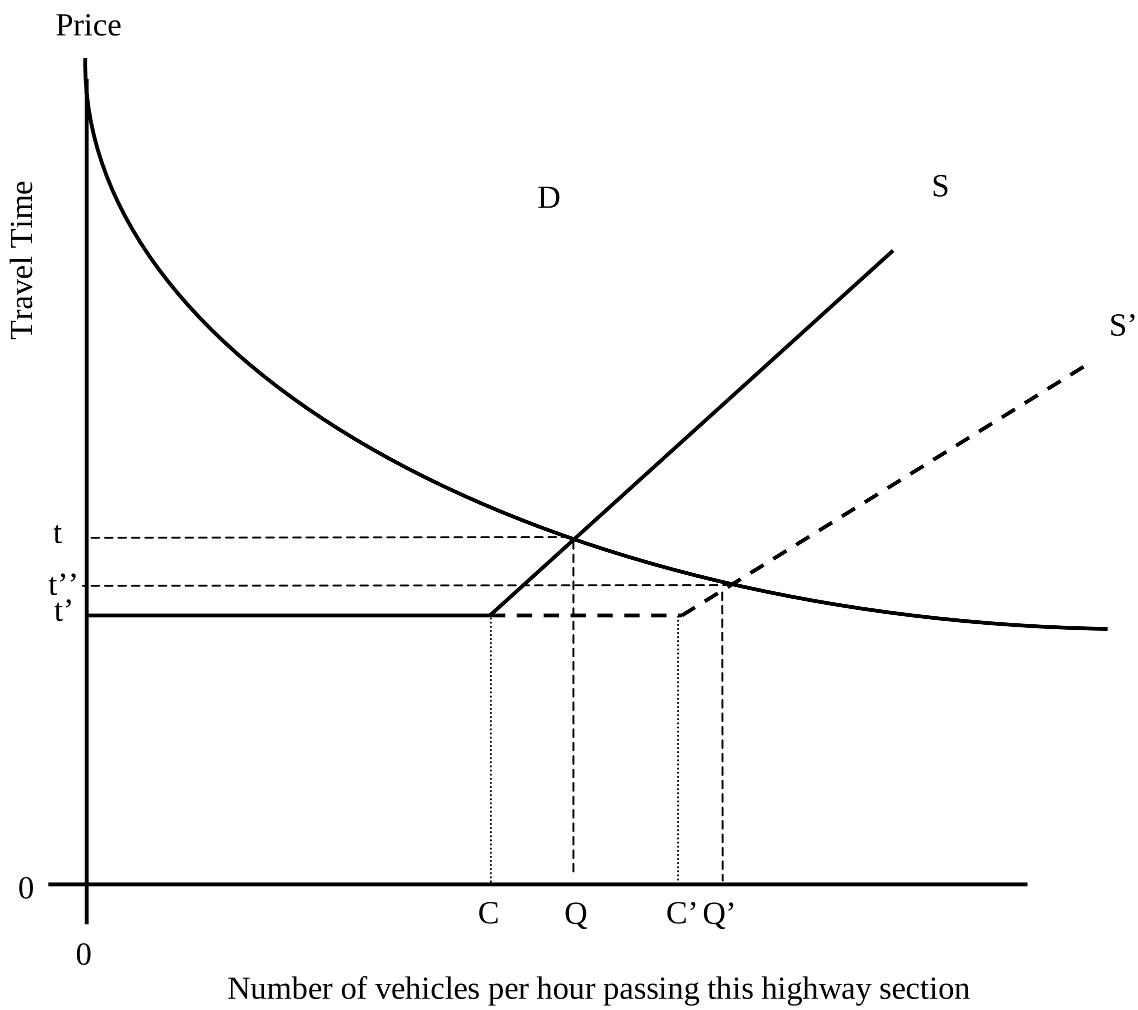


Figure 2 Increased Demand – The demand curve moves from D to D’ increasing the number of vehicles from Q to Q’

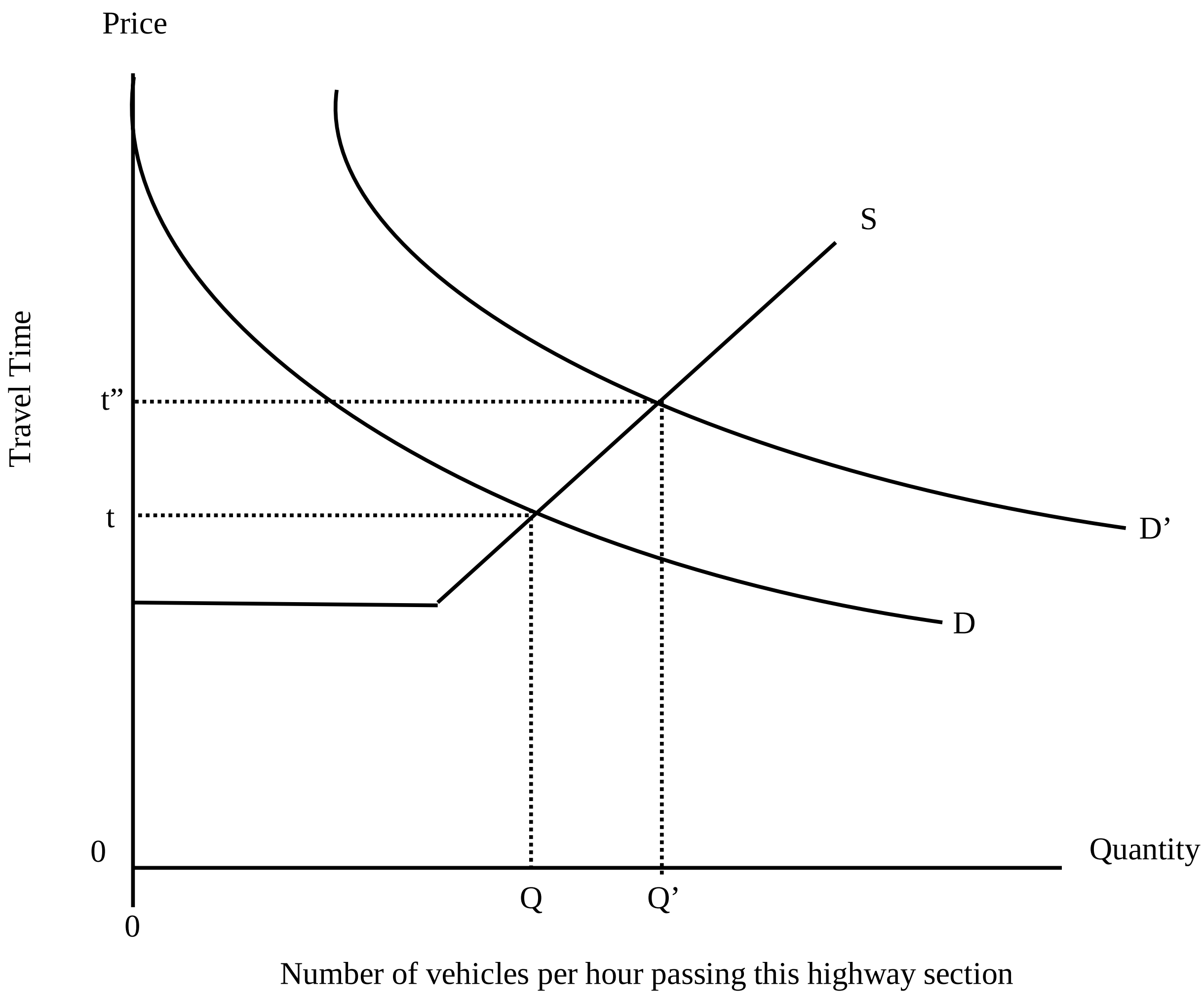
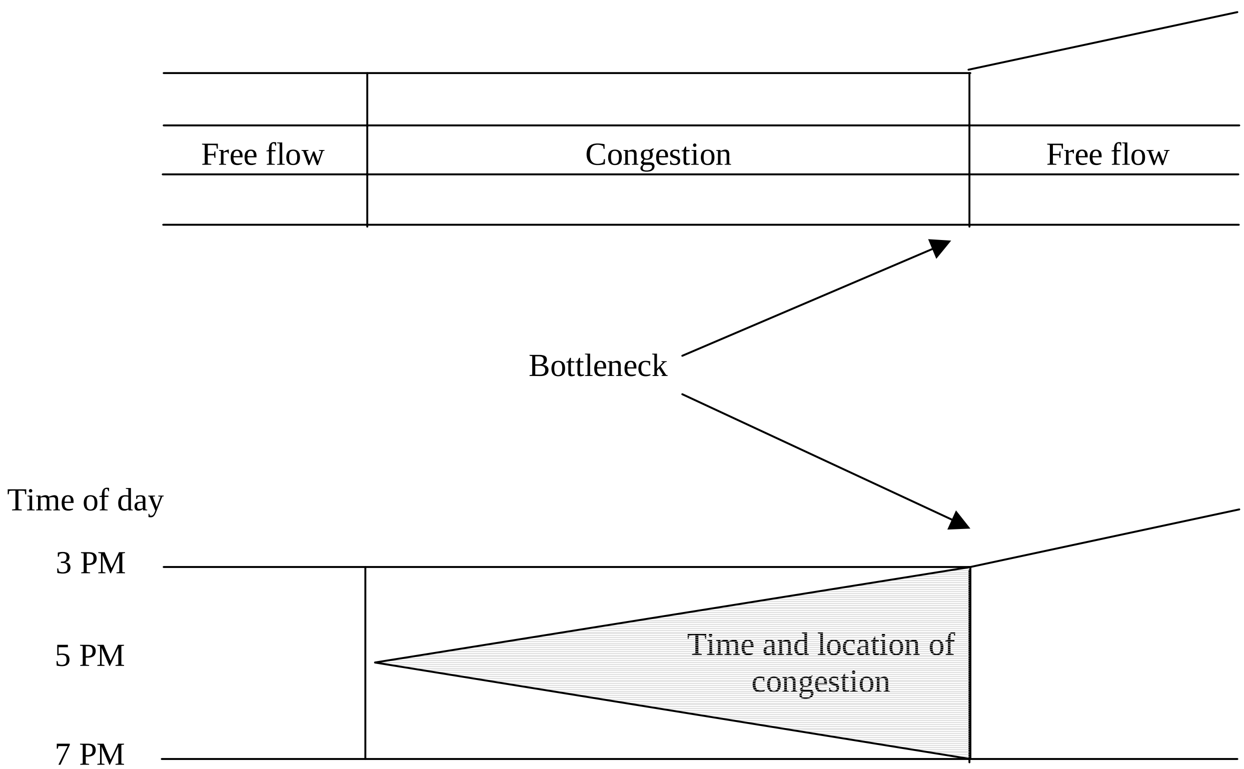


Figure 3 Simple Freeway Segment



Evolution of congestion over the peak period

Figure 4 Model of Freeway Delay

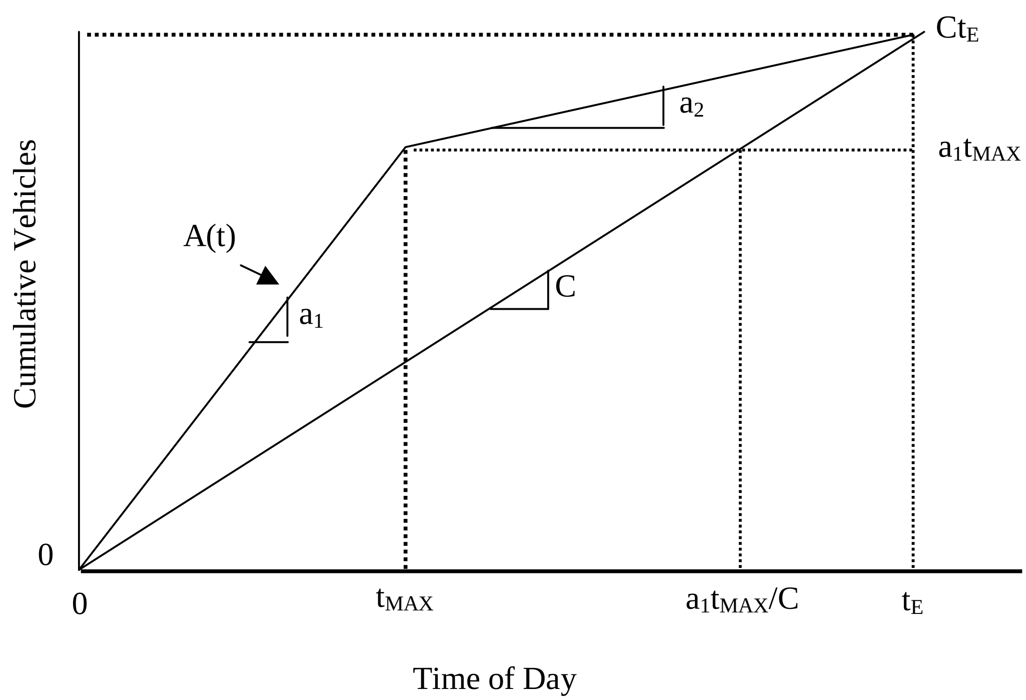
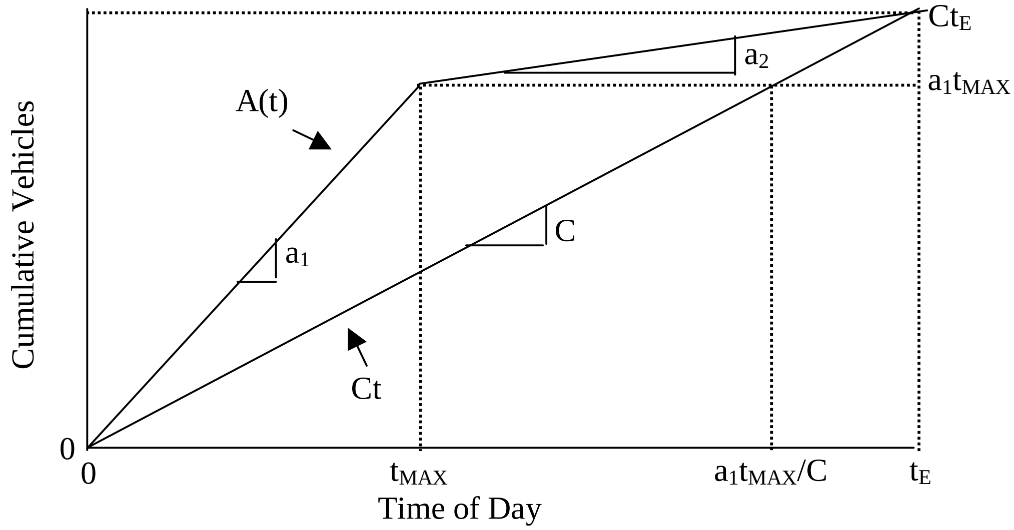
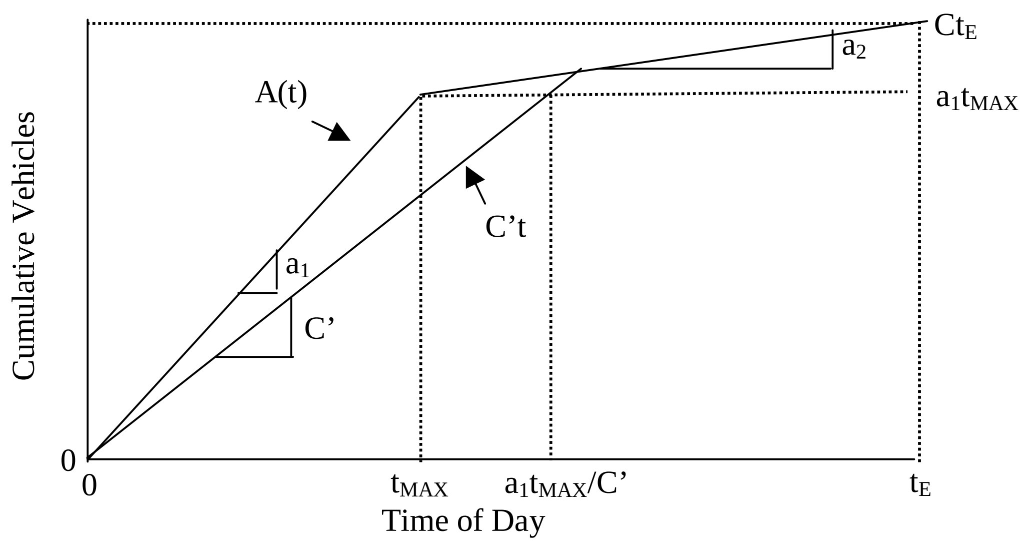


Figure 5 Effects of a Shift in Departure Times on Delay

a. Initial condition



b. After capacity increase but with no shift in departure times



c. After shift in departure times such that freeway delay is not reduced

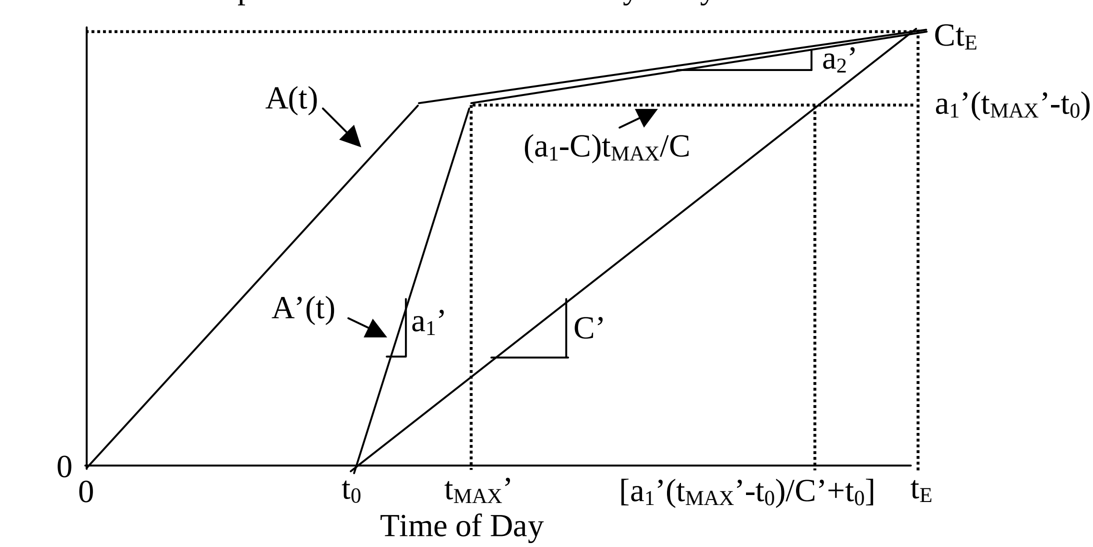


Figure 6

Travel times for primary and linked trips