Chapter 44

Congestion Studies

44.1 Introduction

Transportation system consists of a group of activities as well as entities interacting with each other to achieve the goal of transporting people or goods from one place to another. Hence, the system has to meet the perceived social and economical needs of the users. As these needs change, the transportation system itself evolves and problems occur as it becomes inadequate to serve the public interest. One of the negative impacts of any transportation system is traffic congestion. Traffic congestion occurs wherever demand exceeds the capacity of the transportation system. This lecture gives an overview of how congestion is generated, how it can be measured or quantified; and also the various countermeasures to be taken in order to counteract congestion. Adequate performance measures are needed in order to quantify congestion in a transportation system. Quality of service measures indicates the degree of traveller satisfaction with system performance and this is covered under traveller perception. Several measures have been taken in order to counteract congestion. They are basically classified into supply and demand measures. An overview of all these aspects of congestion is dealt with in this lecture.

44.2 Generation of traffic congestion

The flow chart in Fig. 44:1 shows how traffic congestion is generated in a transportation system. With the evolution of society, economy and technology, the household characteristics as well as the transportation system gets affected. The change in transport system causes a change in transport behaviour and locational pattern of the system. The change in household characteristics, transport behaviour, locational pattern, and other growth effects result in the growth of traffic. But the change or improvement in road capacity is only as the result of change in the transportation system and hence finally a situation arises where the traffic demand is greater

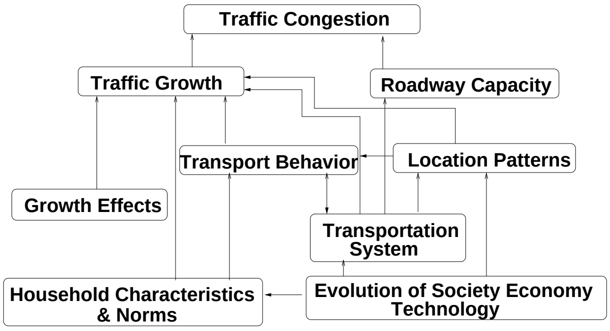
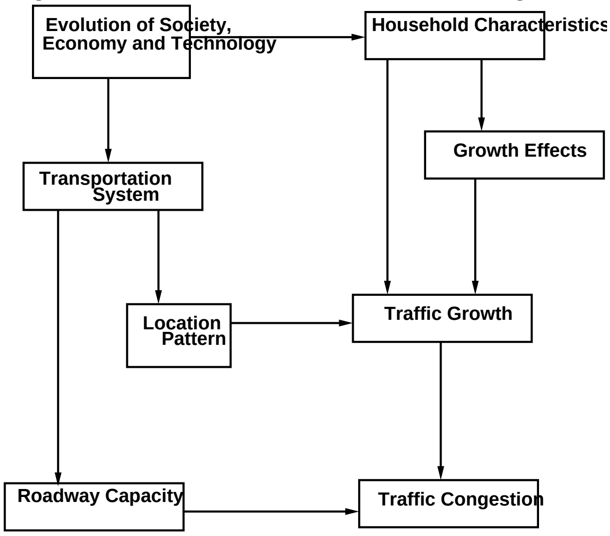


Figure 44:1: Generation of traffic congestion



than the capacity of the roadway. This situation is called traffic congestion.

44.2.1 Effects of congestion

Congestion has a large number of ill effects on drivers, environment, health and the economy in the following ways.

- Drivers who encounter unexpected traffic may be late for work and other appointments causing a loss in productivity and their valuable time.
- Since congestion leads to increase in travel time i,e.,vehicles are made to travel for more time than required which consumes large amount of fuel there by causing fuel loss and economic loss to the drivers.
- One of the most harmful effects of traffic congestion is its impact on the environment. Despite the growing number of vehicles ,cars stopped in traffic still produces a large volume

of harmful carbon emissions . Increase in pollutants (because of both the additional fuel burned and more toxic gases produced while internal combustion engines are in idle or in stop-and-go traffic)

- Drivers who become impatient may be more likely to drive aggressively and dangerously and leads to high potential for traffic accidents
- Negative impact on people's psychological state, which may affect productivity at work and personal relationships
- Slow and inefficient emergency response and delivery services
- Decrease in road surface lifetime: When a vehicle moves over the surface, the areas of contact (where the vehicles' tyres touch the road) are deflected downwards under the weight of the vehicle and as the vehicle moves forward, the deflection corrects itself to its original position.
- Vehicle maintenance costs; 'Wear and tear' on mechanical components of vehicles such as the clutch and brakes is also considerably increased under stop-start driving conditions and hence increasing the vehicle maintenance costs.
- One beneficial effect of traffic congestion is its ability to encourage drivers to consider other transportation options like a subway, light rail or bus service. These options reduce traffic on the roads ,thereby reducing congestion and environmental pollution.

The summation of all these effects yields a considerable loss for the society and the economy of an urban area

44.2.2 Traffic congestion

A system is said to be congested when the demand exceeds the capacity of the section. Traffic congestion can be defined in the following two ways:

1. Congestion is the travel time or delay in excess of that normally incurred under light or free flow traffic condition.
2. Unacceptable congestion is travel time or delay in excess of agreed norm which may vary by type of transport facility, travel mode, geographical location, and time of the day.

Fig. 44:2 shows the definition of congestion. The solid line represents the travel speed under free-flow conditions and the dotted line represents the actual travel speed. During congestion,

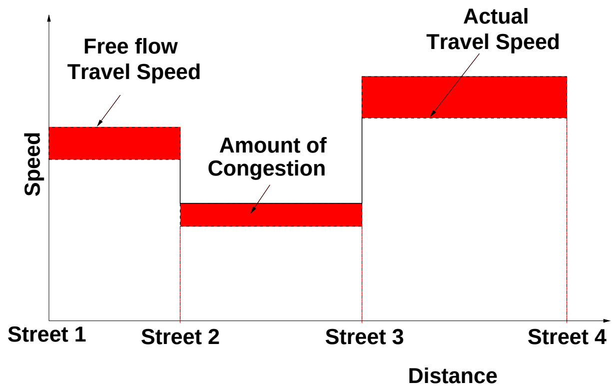


Figure 44:2: Definition of congestion

the vehicles will be travelling at a speed less than their free flow speed. The shaded area in between these two lines represents the amount of congestion. Traffic congestion may be of two types:

1. **Recurrent Congestion**: Recurrent congestion generally occurs at the same place, at the same time every weekday or weekend day. This is generally the consequence of factors that act regularly or periodically on the transportation system such as daily commuting or weekend trips. Recurrent congestion is predictable and typically occurs during peak hours. It displays a large degree of randomness in terms of duration and severity.

2. **Non-Recurrent congestion**: Non-Recurrent congestion is the effect of unexpected ,unplanned large events(road woks, accidents, special events and so on) that affect transportation system more or less randomly and as such,cannot be easily predicted.

44.3 Measurement of congestion

44.3.1 Need and uses of congestion measurement

Congestion has to be measured or quantified in order to suggest suitable counter measures and their evaluation. Congestion information can be used in a variety of policy, planning and operational situations. It may be used by public agencies in assessing facility or system adequacy, identifying problems, calibrating models, developing and assessing improvements, formulating programs policies and priorities. It may be used by private sector in making locational or investment decisions. It may be used by general public and media in assessing traveler's satisfaction.

44.3.2 System performance measurement

Performance measure of a congested roadway can be done using the following four components:

1. Duration,
2. Extent,
3. Intensity, and
4. Reliability.

44.3.3 Duration

Duration of congestion is the amount of time the congestion affects the travel system. The *peak hour* has now extended to peak period in many corridors. Measures that can quantify congestion include:

- Amount of time during the day that the travel rate indicates congested travel on a system element or entire system.
- Amount of time during the day that traffic density measurement techniques (detectors, aerial surveillance, etc.) indicate congested travel.

Duration of congestion is the sum of length of each analysis sub period for which the demand exceeds capacity. This component measures the performance of a particular road in handling traffic efficiently i,e.,with the increase in the duration of congestion, poorer will be the performance of the transportation system. The maximum duration on any link indicates the amount of time before congestion is completely cleared from the corridor. Duration of congestion can be computed for a corridor using the following equation: For corridor analysis,

$$H = N \times T \tag{44.1}$$

where, H is the duration of congestion (hours), N is the number of analysis sub periods for which $v/c > 1$, and T is the duration of analysis sub-period (hours). For area wide analysis,

$$H_i = \frac{T\frac{v_i}{c_i}(1-r)}{1-r(\frac{v_i}{c_i})} \tag{44.2}$$

where, H_i is the duration of congestion for link i (hours), T is the duration of analysis period (hours), r is the ratio of peak demand to peak demand rate, v_i is the vehicle demand on link i (veh/hr), and c_i is the capacity of link i (veh/hr).

Table 44:1: Queue density default values

Subsystem	Storage density (veh/km/lane)	Spacing (m)
Free-way	75	13.3
Two lane highway	130	7.5
Urban street	130	7.5

44.3.4 Extent

Extent of congestion is described by estimating the number of people or vehicles affected by congestion and by the geographic distribution of congestion. These measures include:

1. Number or percentage of trips affected by congestion.
2. Number or percentage of person or vehicle meters affected by congestion.
3. Percentage of the system affected by congestion.

Performance measures of extent of congestion can be computed from sum of length of queuing on each segment. Segments in which queue overflows the capacity are also identified. This is useful for ramp metering analysis. To compute queue length, average density of vehicles in a queue need to be known. The default values suggested by HCM 2000 are given in Table 1. Queue length can be found out using the equation:

$$QL_i = \frac{T(v - c)}{N \times ds} \tag{44.3}$$

where; QL_i is the queue length (meter), v is the segment demand (veh/hour), c is the segment capacity (veh/hour), N is the number of lanes, ds is the storage density (veh/meter/lane), and T is the duration of analysis period (hour). If $v < c$, Q_i=0 The equation for queue length is similar for both corridor and area-wide analysis.

Numerical example

Consider a road segment of 6 lanes with a capacity of 2400 veh/hr/lane. It is observed that the storage density is 75 veh/meter and the segment demand is found to be 2800 veh/hr/lane. Given that the duration of analysis sub period is 2 hrs calculate the queue length that is formed due to congestion.

Solution The queue length of a particular road segment is given by,

$$QL = \frac{T \times (v - c)}{N \times ds} \tag{44.4}$$

It is given that Number of lanes, N=6, Duration of analysis sub period, T= 2 hrs, Segment Capacity=c=2400 veh/hr/lane, Segment Demand=v=2800 veh/hr/lane, Storage Density=ds=75 veh/meter. Now,the queue length can be calculated by using the above formula as follows: $QL = 2 * (2800 - 2400) * 6/(6 * 75) = 10.667mts$ Therefore, the extent of congestion in terms of queue length is 10.667mts

44.3.5 Intensity

Intensity of congestion marks the severity of congestion. It is used to differentiate between levels of congestion on transport system and to define total amount of congestion. It is measured in terms of:

- Delay in person hours or vehicle hours;
- Average speed of roadway, corridor, or network;
- Delay per capita or per vehicle travelling in the corridor, or per person or per vehicle affected by congestion;
- Relative delay rate (relative rate of time lost for vehicles);

Intensity in terms of delay is given by,

$$D_{PH} = T_{PH} - T^0_{PH} \tag{44.5}$$

where, D_{PH} is the person hours of delay, T_{PH} is the person hours of travel under actual conditions, and T^0_{PH} is the person hours of travel under free flow conditions. The T_{PH} is given by:

$$T_{PH} = \frac{O_{AV} \times v \times l}{S} \tag{44.6}$$

where, O_{AV} is the average vehicle occupancy, v is the vehicle demand (veh), l is the length of link (km), and S is the mean speed of link (km/hr). The T_{PH} is given by:

$$T^0_{PH} = \frac{O_{AV} \times v \times l}{S_0} \tag{44.7}$$

where, O_{AV} is the average vehicle occupancy, v is the vehicle demand (veh), l is the length of link (km), and S_0 is the free flow speed on the link (km/hr)

Numerical example

On a 2.8 km long link of road, it was found that the demand is 1000 Vehicles/hour mean speed of the link is 12 km/hr, and the free flow speed is 27 km/hr. Assuming that the average vehicle occupancy is 1.2 person/vehicle, calculate the congestion intensity in terms of total person hours of delay.

Solution: Given data: Length of the link=l=2.8 km, Vehicle demand=v=1000 veh, Mean Speed of the link=S=12 km/hr, Free flow speed on the link=So=27 km/hr, and Average Vehicle Occupancy=AVO=1.2 person/veh. Person hours of delay is given as

$$D_{PH} = T_{PH} - T^0_{PH}$$

Person hours of travel under actual conditions,

$$\begin{aligned} T_{PH} &= \frac{O_{AV} \times v \times l}{S} \\ &= \frac{1.2 \times 1000 \times 2.8}{12} \\ &= 280 \text{ person hours} \end{aligned}$$

Person hours of travel under free flow conditions,

$$\begin{aligned} T^0_{PH} &= \frac{O_{AV} \times v \times l}{S_0} \\ &= \frac{1.2 \times 1000 \times 2.8}{27} \\ &= 124.4 \text{ person hours} \end{aligned}$$

Therefore, person hours of delay can be calculated as follows,,

$$\begin{aligned} D_{PH} = &= 280 - 124.4 \\ &= 155.6 \ \text{ person hours} \\ &= 156 \text{ person hours (approx).} \end{aligned}$$

Hence, the intensity of congestion is determined in terms of person hours of delay as 156 person hours.

44.3.6 Relationship between duration, extent, and intensity of congestion

The variation in extent and duration of congestion indicates different problems requiring different solutions. Small delay and extent indicates limited problem, small delay for large extent

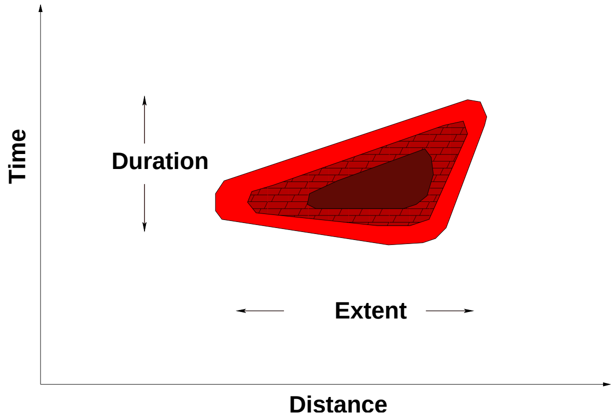


Figure 44:3: Intensity of congestion-relation between duration and distance

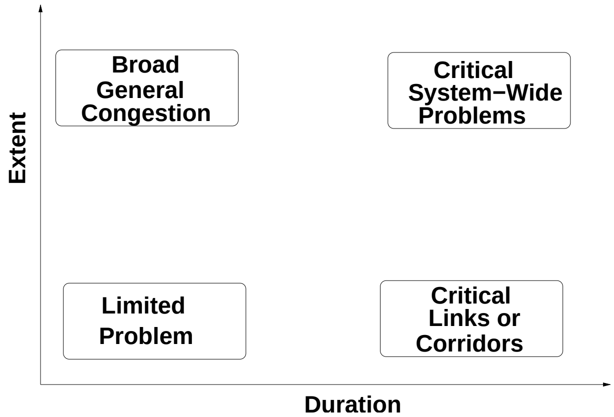


Figure 44:4: Intensity of congestion-Relation between extent and duration of delay

indicates general congestion, great delay for small extent indicates critical links and great delay for large extent indicates critical system-wide problem. Fig. 44:3 also illustrates the relationship between duration, extent and intensity The extent of congestion is seen on the x-axis, the duration on the y-axis. The intensity is shown in the shading. Based on the extent and duration the congestion can be classified into four types as shown in Fig.44:4. Fig.44:3 indicates a time distance graph with the shaded area indicating congestion in individual road segments for discrete time periods. The figure shows the relationship between duration, extent, and intensity. The product of extent and duration indicates the intensity, or magnitude of the congestion problem.

44.3.7 Reliability

Reliability is a measure of a drivers ability to accurately predict and plan for a certain travel time. The more unexpected events that occur on a roadway, the less reliable it is. Non recurrent congestion has a bigger impact on the reliability of the roadway relative to concurrent congestion. In other words, Travel-time reliability is defined as the level of consistency in travel conditions over time and is measured by describing the distribution of travel times that occur over a substantial period of time. Reliability is an important component of roadway performance and perhaps more importantly, of motorists perceptions of roadway performance. The importance of measuring and managing reliability in reducing congestion is explained as follows.

- Motorists have less tolerance for unexpected delay than for expected delay
- Cost associated with unreliable travel
- Reliability is a valued service in other industries and utilities

Therefore, it is clear that reliability is the impact of non-recurrent congestion on transport system and it can be expressed as average travel rate or speed standard deviation or delay standard deviation.

44.4 Congestion countermeasures

Fully eradicating roadway congestion is neither an affordable, nor feasible goal in economically dynamic urban areas. However, much can be done to reduce its occurrence and to lessen its impacts on roadway users within large cities congestion is a phenomenon that can be better and more effectively managed. There are many possible measures that can be deployed to treat or mitigate congestion.

44.4.1 classification

Congestion countermeasures include supply measures and demand measures.,which will be discussed in detail in the next section. Other than these two measures, an additional longer-term tool used against traffic problems is land-use planning and policy. It has the potential

- To control the number and growth of major traffic generators along congestion corridors.
- To establish sensible allocations of land for future development given present constraints and expansion plans for the transportation network and

- To enforce balanced employment and residential development, thus reducing the long home-to-work trips.

44.4.2 Supply measures:

They add capacity to the system or make the system operate more efficiently. They focus on the transportation system. All measures in this category supply capacity so that demand is better satisfied and delays and queuing are lessened. Supply measures include

1. Development of new or expanded infrastructure: This includes civil projects (new freeways, transit lines etc), road widening, bridge replacements, permanent freeway lane conversions, technology conversions(a new rail technology, a modernized bus fleet and ITS)

2. Small scale capacity and efficiency improvements: This includes signal system upgrade and coordination, freeway ramp metering, re-location of bus stops, lane management schemes, bottleneck elimination through channelization and operational improvements.

44.4.3 Demand measures:

Demand measures focuses on motorists and travelers and attempt to modify their trip making behaviour. All the measures that are employed in this category aim to modify travel habits so that travel demand is considerably reduced or switch to other modes,other times or other locations that have more capacity to accommodate it. The demand measures include Congestion pricing, Parking pricing and Restrictions on vehicle ownership and use. Congestion pricing is the method in which users are charged on congested roads. This is discussed in detail in the next section. Parking pricing discourages use of private vehicles to specific areas. It includes heavy import duties, separate licensing requirement, heavy annual fees, expensive fuel prices, etc to restrain private vehicle acquisition and use. Heavy annual fees, strict periodic inspections and expensive fuel prices also restrict use of private vehicles. Intelligent Transportation systems (ITS) provide tools for implementation of both supply and demand congestion measures. Supply type ITS tools include early incident detection and resolution, optimized signal operation based on real time demand, freeway management with ramp metering, accident avoidance with variable message signs(VMS) warning of upcoming conditions(congestion, fog etc.,) and bus system coordination. Demand-type ITS include the provision of real-time traffic congestion information at various places for informed travel decisions.

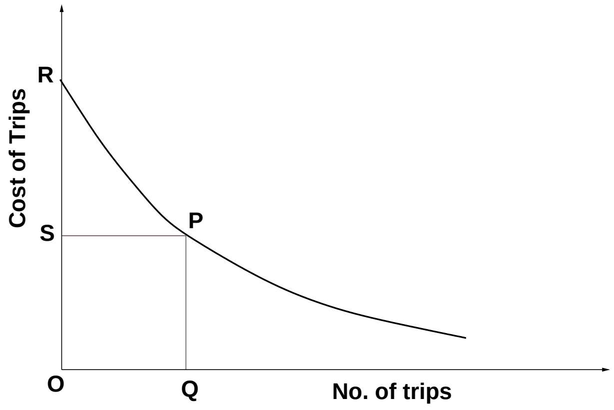


Figure 44:5: Demand Curve

44.4.4 Congestion pricing

Congestion pricing is a method of road user taxation, charging the users of congested roads according to the time spent or distance travelled on those roads. The principle behind congestion pricing is that those who cause congestion or use road in congested period should be charged, thus giving the road user the choice to make a journey or not.

Economic principle behind congestion pricing

Journey costs include private journey cost, congestion cost, environmental cost, and road maintenance cost. The benefit a road user obtains from the journey is the price he prepared to pay in order to make the journey. As the price gradually increases, a point will be reached when the trip maker considers it not worth performing or it is worth performing by other means. This is known as the critical price. At a cost less than this critical price, he enjoys a net benefit called as consumer surplus(es) and is given by:

$$s = x - y \tag{44.8}$$

where, x is the amount the consumer is prepared to pay, and y is the amount he actually pays. The basics of congestion pricing involves demand function, private cost function as well as marginal cost function. These are explained below.

Demand

Fig. 44:5 shows the general form of a demand curve. In the figure, area QOSP indicates the absolute utility to trip maker and the area SRP indicates the net benefit.

Private cost

Total private cost of a trip, is given by:

$$c = a + \frac{b}{v} \tag{44.9}$$

where, a is the component proportional to distance, b is the component proportional to speed, and v is the speed of the vehicle (km/h). In the congested region, the speed of the vehicle can be expressed as,

$$v = d - eq \tag{44.10}$$

where, q is the flow in veh/hour, d and e are constants.

Marginal cost

Marginal cost is the additional cost of adding one extra vehicle to the traffic stream. It reduces speed and causes congestion and results in increase in cost of overall journey. The total cost incurred by all vehicles in one hour(C_T) is given by:

$$C_T = cq \tag{44.11}$$

Marginal cost is obtained by differentiating the total cost with respect to the flow(q) as shown in the following equations.

$$M = \frac{d(cq)}{dq} = c + q\frac{dc}{dq} \tag{44.12}$$

$$\frac{dc}{dq} = \frac{dc}{dv} \times \frac{dv}{dq} \tag{44.13}$$

$$= (-b)/v^2 \times -e \tag{44.14}$$

$$= be/v^2 \tag{44.15}$$

$$\frac{d(cq)}{dq} = c + q\frac{dc}{dq} \tag{44.16}$$

$$= a + \frac{b}{v} + \frac{d-v}{e} \times \frac{be}{v^2} \tag{44.17}$$

Note that c and q in the above derivation is obtained from Equations 44.9 and 44.10 respectively. Therefore the marginal cost is given as:

$$M = a + \frac{b}{v} + \frac{(d-v)b}{v^2} \tag{44.18}$$

Fig. 44:6 shows the variation of marginal cost per flow as well as private cost per flow. It is seen that the marginal cost will always be greater than the private cost, the increase representing the congestion cost.

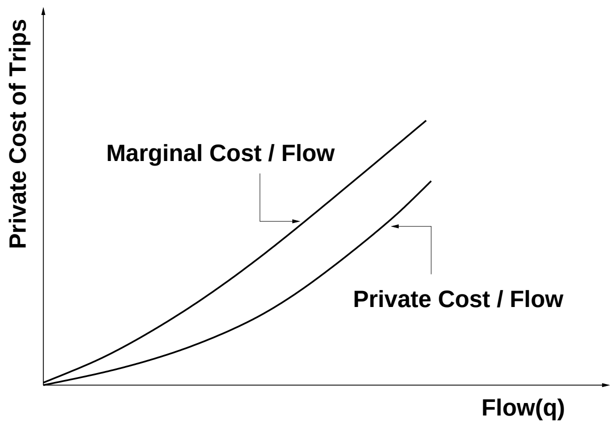


Figure 44:6: Private cost/flow and cost and marginal curve

Equilibrium condition and Optimum condition

Superimposing the demand curve on the private cost/flow and marginal cost/flow curves, the position as shown in Fig. 44:7 is obtained. The intersection of the demand curve and the private costs curve at point A represents the equilibrium condition, obtained when travel decisions are based on private costs only. The intersection of the demand curve and the marginal costs curve at point B represents the optimum condition. At this point the flow Q_0 corresponds to the cost C_0 which is the marginal cost as well as the value of the trip to the trip maker. The net benefit under the two positions A and B are shown by the areas ACZ and BYC_YZ respectively. If the conditions are shifted from point A to B, the net benefit due to change will be given by area CC_yYX minus AXB. If the area CC_yYX is greater than arc AXB, the net benefit will be positive. The shifting of conditions from point A to B can be brought about by imposing a road pricing charge BY. Under this scheme, the private vehicles continuing to use the roads will on an average be worse off in the first place because BY will always exceed the individual increase in benefits XY.

44.4.5 Numerical example

Vehicles are moving on a road at the rate of 500 vehicle/hour, at a velocity of 15 km/hr. Find the equation for marginal cost.

Solution: Private cost of the trip is given by,

$$\begin{aligned} c &= \frac{a+b}{v} \\ &= \frac{a+b}{15} \end{aligned}$$

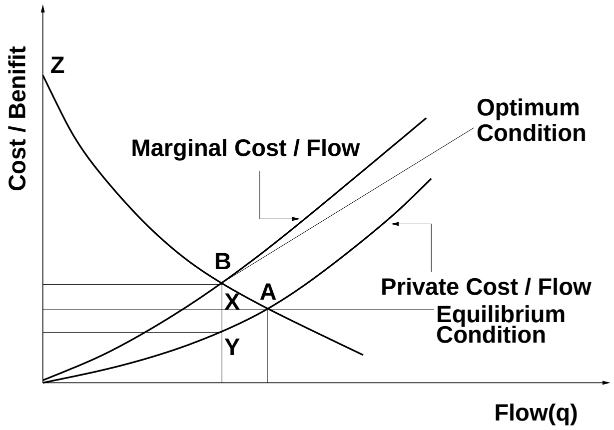


Figure 44:7: Relation between material cost, private cost and demand curves.

It is given that Flow rate, q=500 veh/hr. Speed of the vehicle is given by,

$$\begin{aligned} v &= d - eq \\ &= d - 500e \end{aligned}$$

Marginal Cost is given by,

$$\begin{aligned} M &= a + \frac{b}{v} + \frac{(d-v)b}{v^2} \\ &= a + \frac{b}{15} + \frac{(d-15)b}{225} \end{aligned}$$

Therefore, the equation of marginal cost for the vehicles moving on the given congested road is given by $M = a + (b/15) + [(d-15) * b/225]$

44.4.6 Uses of congestion pricing

1. Diverts travelers to other modes
2. Causes cancellation of non essential trips during peak hours
3. Collects sufficient fund for major upgrades of highways and other road maintenance works.
4. Cross-subsidizes public transport modes thereby fetching income to the government.

44.4.7 Requirements of a good pricing system

1. Charges should be closely related to the amount of use made of roads
2. Price should be variable at different times of day/week/year or for different classes of vehicles
3. It should be stable and ascertainable by road users before commencement of journey
4. Method should be simple for road users to understand and police to enforce
5. Should be accepted by public as fair to all
6. Payment in advance should be possible
7. Should be reliable
8. Should be free from fraud or evasion
9. Should be capable of being applied to the whole country

44.5 Conclusion

Causes and effects of congestion along with various performance measures and with many other counter measures are discussed in detail considering the actual or technical definition of congestion. The congestion performance measures described are generalized measures. There are several other performance measures and indices. Advanced study on congestion can include improved measurement schemes and the combined travel demand modeling and route choice under congested conditions. With the implementation of all the counter measures traffic congestion, the most pronouncing problem of transportation may be reduced or controlled to certain extent. The principle and process of congestion pricing was also discussed with the help of certain graphs..

44.6 References

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