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Evaluation of Road Traffic Congestion by Shock Wave Theory and Reduction Strategies

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Abstract: Road traffic congestion continues to remain a major problem in most cities around the world, especially in developing countries resulting in extensive delays, improved fuel wastage and financial losses. Urban traffic congestion has been a difficult problem in the growth of modern cities in India. The factors that reason the traffic congestion are complex and they mutually restrict. Transportation researchers have long struggled to find adequate ways of describing and analysing traffic congestion, as marked from the large number of often challenging approaches and models that have been developed. In this study, we explain traffic flow model with shockwave theory and operational strategies to manage traffic congestion in developing countries like India. Monitoring traffic density and speed helps to better manage traffic flow and plan transport infrastructure and policy. In this study, we present techniques to measure traffic density and speed in unplanned traffic, common in developing countries, and apply those techniques to better understand traffic patterns.

Keywords: *Road traffic**,** Traffic congestion, Traffic flow model, shockwave theory*.

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Introduction: In many large and medium size cities traffic congestion problem has become more and more severe day by day. In many regions during peak hours traffic is much slower than the expected flow. It is very necessary that the traffic congestion problems can be effectively identified; otherwise it will affect the day to day functioning of people of the society resulting in many inconveniences. Therefore there is a need of accurate and effective solution to traffic congestion problem has become crucial.

There is no single specific definition of traffic congestion. Congestion is the impendence vehicles impose on each other due to speed flow relationship in condition where the use of transport system approaches capacity. It is the essentially a relative phenomenon that is linked to the difference between the roadway system performance that people expect and how the system actually performs. A better way to defining excessive congestion is: When the marginal costs to society of congestion exceed the marginal costs of efforts reduce congestion such as adding to road or other transport infrastructure is excessive and action to manage it batter warranted.[3]

This study presents a model to represent traffic congestion based on shock wave theory. In the literature of transport studies there are two main approaches to modelling traffic congestion on a roadway – The traffic flow model and the shock wave and bottleneck model.

The traffic flow model is based on relationship between traffic flow rate and i.e. number of vehicles entering the road within a certain period of time and speed. In this model travel time cost is a function of the traffic flow rate and on the other hand the other hand the shock wave bottleneck model, first developed by Vickery(1969), describes as the congestion mechanism as queuing behind a bottleneck, travel time is waiting time within the queue.

Traffic Flow Congestion:

The road traffic flow can be characterized by three variables using traffic flow, traffic density and speed of vehicle through an analogy with fluid dynamics. In this model the traffic is represented as a compressible fluid and movement of individual vehicle cannot be monitored

The relationship between these variables given by the following equation:[2]

$$V = f(D) \qquad \text{-------------------------} \ (1)$$

$$Q = D \times V \qquad \text{---------------------------} \ (2)$$

Where Q: Traffic volume (vehicle/hour)

D: Traffic Density (vehicle/Km)

V: Speed of vehicle (Km/hour)

With $Q = \frac{1}{h}$ and $D = \frac{1}{S}$ Where h (hour) time in the succession interval, S (Km) is the distance between successive vehicle.

Now total traffic volume in (vehicle/km)

$Q_T = \sum$ Mi (Mi – Mileage of i type vehicle)

$= \sum$A (Mi) (A (Mi) – Average Mileage of i type vehicle)

= A (Mi) ×N (N- total no of vehicles.)

And $Q_{total} = \sum Q_T$ on a road link.

$= \sum$ Q on a road link× Tp×R_l

Where Q- Traffic volume (in vehicle/time unit),T_p- Time period, R_l-Length of road link.[2]

Since, in the macroscopic approach the traffic is treated as a continuous flow, It is not possible to get a detailed representation of travel speed variation associated with individual or categories of motor vehicle type, which compose the traffic flows.

Shockwaves in traffic flow:

Shockwaves that occur in traffic flow are very similar to the waves produced by dropping stone in water. A Shockwave propagates along a line of vehicles in response to changing conditions at the front of the line. Shockwave can be generated by collision. Sudden increase in speed caused by entering free flow conditions or by a number means. Basically a shockwave exists whenever the traffic conditions change. The equation that is used to estimate the propagation velocity of shock waves is given below:

$$V_{sw} = \frac{q_b - q_a}{k_b - k_a}$$

Where V_{sw} - Propagation velocity of shockwave (Mile/hour)

q_b - Flow before change in condition. (Vehicle /hour)

q_a - Flow after change in condition. (Vehicle / hour)

k_{b-} Traffic density before change the condition

k_a - Traffic density after change the condition

Note that the magnitude and direction of the shock wave:

(+) – Shockwave travelling in same direction as traffic stream

(-) - Shockwave travelling in opposite direction as traffic stream

The fundamental diagram of traffic flow for two adjacent sections of a roadway with different capacities (maximum flows) is shown in Figure 1.

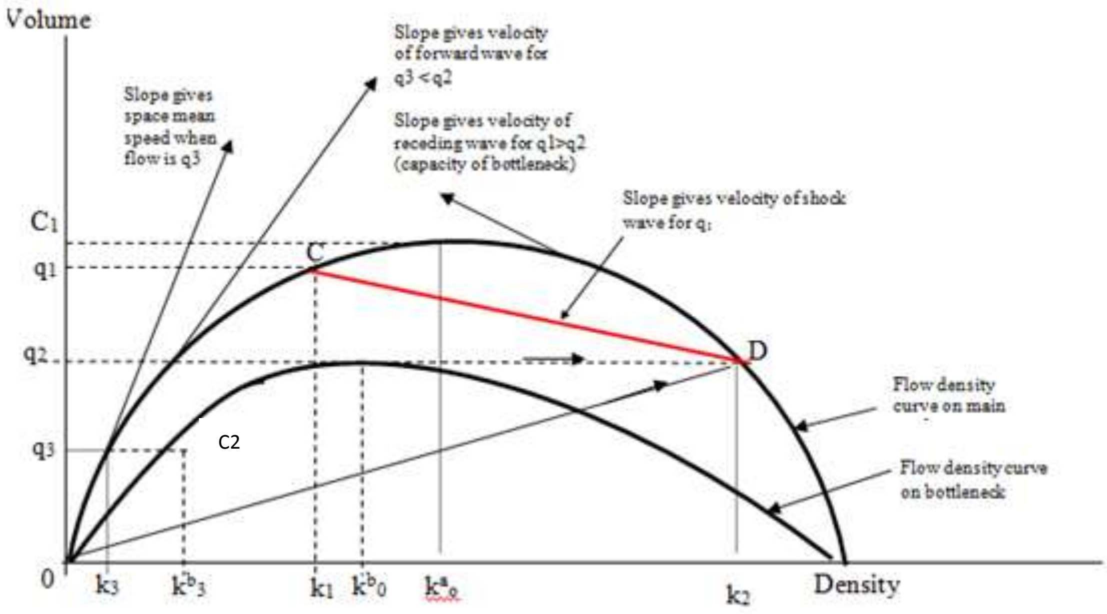

Figure 1. Kinematic and Shock Wave Measurements Related to Flow-Density Curve

This figure describes the phenomenon of backups and queuing on roadway due to sudden reduction of the capacity of the highway (known as a bottleneck condition).[6]
The sudden reduction in capacity could be due to

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- Accidents
- reduction in the number of lanes
- restricted bridge sizes
- work zones
- a signal turning red, and so forth

In this situation, the capacity on the roadway suddenly changes from C_1 to a lower value of C_2 with a corresponding change in optimum density from K_0^a to a value of K_0^b. When such a condition exists and the normal flow and density on the roadway are relatively large, the speeds of the vehicles will have to be reduced while passing the bottleneck. The point at which the speed reduction takes place can be approximately noted by the turning on of the brake lights of the vehicles.

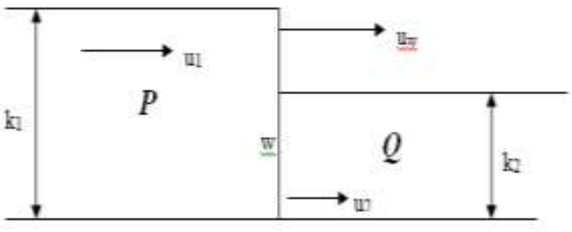

Figure2. Movement of Shock Wave due to change in Densities

Let us consider two different densities of traffic, k_1 and k_2, along a straight roadway as shown in Figure 2. where $k_1 > k_2$, also assume that these densities are separated by the line w, representing the shock wave moving at a speed U_w. If the line w moves in the direction of the arrow (that is, in the direction of the traffic flow), U_w is positive, With $\mathbf{u_1}$ equal to the space mean speed of vehicles in the area with density $\mathbf{k_1}$ (section P), the speed of the vehicle in this area relative to the line w is[6]

$$u_{r1} = (u_1 - u_w)$$

The number of vehicles crossing the line w from area P during a time period t is

$$N_1 = u_{r1} k_1 t$$

Similarly, the speed of vehicles in the area with density $\boldsymbol{k_2}$ (section Q) relative to line ***w*** is

$u_{r2} = (u_2 - u_w)$

and the number of vehicles crossing line ***w*** during a time period t is

$$N_2 = u_{r2} k_2 t$$

Since the net change is zero that is, $N_1 = N_2$

$$\rightarrow \; (u_1 - u_w)k_1 = (u_2 - u_w)k_2$$

we have

$$u_2k_2 - u_1k_1 = u_w(k_2 - k_1) \qquad \text{------------------------(3)}$$

if the flow rates in sections P and Q are $\mathbf{q_1}$ and $\mathbf{q_2}$, respectively, then

$$q_1 = k_1u_1 \text{ and } q_2 = k_2u_2$$

Substituting q_1 and q_2 for k_1u_1 and k_2u_2 in Eq. 3 gives

$$q_2 - q_1 = u_w (k_2 - k_1)$$

That is,

$$u_w = (q_2 - q_1)/(k_2 - k_1)$$

which is also the slope of the line CD shown in Figure 1.

This indicates that the velocity of the shock wave created by a sudden change in density from k_1 to k_2 on a traffic stream is the slope of the chord joining the points associated with k_1 and k_2 on the volume density curve for the traffic stream. Shockwave describes the boundary between two traffic states that are characterized by different densities, speeds and/or flow rates. Shockwave theory describes the dynamics of shockwaves, in other words how the boundary between two traffic states moves in time and space.

Shockwave theory provides a simple means to predict traffic conditions in time and space.

These predictions are largely in line with what can be observed in practice, but they have their limitations.[5]

- Traffic driving away from congestion does not accelerate smoothly towards the free speed but continues driving at the critical speed.
- Transition from one state to the other always occurs in jumps, not taking into account the bound acceleration characteristics of real traffic.
- There is no consideration of hysteresis.
- There are no spontaneous transitions from one state to the other.
- Location of congestion occurrence is not in line with reality.

As a result, more advanced approaches have been proposed. Let us now consider the most important ones.

Continuum traffic flow models: Continuum traffic flow deals with traffic flow in terms of aggregate variables, such as flow, densities and mean speeds. Usually, the models are derived from the analogy between vehicular flow and the flow of continuous media (e.g. fluids or gases), complemented by specific relations describing the average macroscopic properties of traffic flow (e.g. the relation between density and speed). Continuum flow models generally have a limited number of equations that are relatively easy to handle.

Most continuum models describe the dynamics of density $k = k(x, t)$, mean instantaneous speed $u = u(x, t)$ and the flow $q = q(x, t)$. The density $k(x, t)$ describes the expected number of vehicles per unit length at instant t. The flow $q(x, t)$

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equals the expected number of vehicles fl owing past cross-section x during the time unit. The speed $u(x, t)$ equals the mean speed of the vehicle defined according to $q = ku$. Some macroscopic traffic flow models also contain partial differential equations of the speed variance $q = q(x, t)$, or the traffic pressure $P = P\ (x,\ t) = rq$. For an overview of continuum flow models, we refer to Hoogendoorn and Bovy (2001).[5]

Conceptual frameworks used to assess impacts of Congestion: Congestion involves queuing, slower speeds and increased travel times, which impose costs on the economy and generate multiple impacts on urban regions and their inhabitants. Congestion also has a range of indirect impacts including the marginal environmental and resource impacts of congestion, impacts on quality of life, stress, and safety as well as impacts on non vehicular road space users such as the users of sidewalks and road frontage properties. Policy-makers should ensure that cost-benefit evaluations or other policy evaluation methodologies include an assessment of these impacts as well as take into account broader considerations such as the type of cities people want**.**

There is rarely a uniform conceptual framework for addressing congestion and appraising congestion management policies across the variety and scope of actors involved. Furthermore, there exists a real tension between different conceptual models underlying congestion cost and impact calculations which in turn can influence congestion management approaches.

Generally speaking, ***traditional approaches*** used by road administrations have focused on managing road systems in urban areas in ways that maximise their ability to handle current and expected future traffic demand. Such *flow-based approaches* seek to maximise the physical usage of available road capacity, taking into account other road management goals such as safety. Roads are rated at a set capacity as expressed in flow, density or, synthetically, as “levels of service”. Achieving higher flows, higher densities and higher levels of service in keeping with the rated capacity of the roadway has traditionally been seen as performance “improvement”. Such operational approaches are well adapted to identifying the locations where bottlenecks exist. They aim to minimise traffic delays and the associated personal, business and resource impacts including personal and productive time lost, fuel wasted and adverse air quality.[9]

There are differences between the outcomes that result from the conceptual frameworks traditionally used and optimal congestion approaches. There are also gaps between the theory and the practice in determining the “optimum” levels of traffic that policy-makers should be aware of when adopting conceptual models to describe congestion and prescribe policy actions. Another gap exists between the design of many congestion management policies and road users’ concerns relating to the reliability and predictability of travel times and not just their average duration. Unreliable travel times impose real costs on individual road users and can have significant downstream impacts on productivity. These impacts and costs should not be neglected when formulating congestion policy responses.

The impacts of congestion are not abstract – they must be linked to roadway users’ experiences and expectations. Instead of attempting to calculate the “overall cost” of congestion, from an analytical viewpoint, it may be more productive to estimate the relative changes in levels and costs of congestion.[4]

Measures to better manage traffic congestion: Effectively managing congestion requires both a holistic and integrated strategy that goes beyond the visible incidence of congestion “on the road” and extends to the management of the developing region as a whole. While there are many possible measures that can be deployed to “treat” or mitigate congestion, there is no single perfect solution.

There are many potential congestion management strategies but most fall into one of two categories – those that provide new capacity or free up existing capacity and those that cap, limit or otherwise manage traffic levels on the new or freed-up capacity.

The latter category of measures broadly encompasses some different but related approaches:[3]

- Improving traffic operations
- Improving public transport
- Implementing mobility management
- Modifying existing infrastructure
- Building new infrastructure

Conclusion: In view of traffic flow model it is clear that the model is an essential tool to assist and enable the traffic and transportation engineers to understand the properties of traffic flow on our roadways so as to design attentive, effective and operational street and highways thus making the roadways easier to drive on. This study presents a dynamic model of traffic congestion based on shockwave theory and some specific operational strategies to manage road traffic in developing countries. It is commonly observed that the flow rate at the bottleneck is not constant but decreasing with queue length. If the traffic volume passing through the bottleneck without a queue is larger than that with a queue, tolling to remove the queue may improve private safety. Yang and Huang (1997) attempt to deal with this problem by assuming that the bottleneck capacity is a decreasing function of the queue length.[1] Rather than assuming the capacity as an exogenously given function. The car following model (e.g., Verhoef (2002)) may be a promising tool to deal with this problem. Technical measures alone are insufficient to ensure the desired

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reduction of traffic congestion it also requires operational strategies to manage traffic congestion.

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