ADVANCES IN TRANSPORTATION STUDIES
An International Journal

Editor in Chief

Andrea Benedetto

Section A & B

Vol. XIX • November 2009

Contents

Section A

Section B

ADVANCES IN TRANSPORTATION STUDIES

An International Journal

Section A

Information-based predictive congestion control for intelligent transportation management

A. Bhattacharyya A. Seetharam M. K. Naskar

Advanced Digital and Embedded Systems Lab, Department of Electronics and Telecommunications Engineering, Jadavpur University, Kolkata, India
email: abhishek.bhattacharyyya@gmail.com, anandsthrm@yahoo.co.in

subm. 28th May 2008 *approv. after rev. 26th June 2009*

Abstract

Third world cities are overpopulated and the number of vehicles plying on roads far exceeds the available traffic handling facilities resulting in frequent traffic congestions. Billions of dollars are being spent by the governments to construct over bridges for traffic management. This work proposes a unique solution scheme in which current traffic information is gathered through inductive loop detectors, piezoelectric sensors and wireless sensor networks coupled with mobile telephony to predict traffic flow and control traffic dynamics. The device placements in turn are dependent on information concerning traffic history of the place. The scheme is modeled on the basis of load-based packet switching as in computer network theory and is cost-effective, business-oriented and hence sustainable and replicable. This work proves the effectiveness of the solution both mathematically and through simulated traffic dynamics for Jadavpur and Gariahat , two heavily congested test cases in Calcutta, India. This is the first information-based decision making scheme which predicts the future for current congestion control using an integrated architecture of in-vogue techniques, sensor and cellular networks.

Keywords – Intelligent Transportation Systems (ITS), wireless sensor networks, inductive loop detector, weigh-in-motion

1. Introduction

Low-cost solutions to growing congestion problems are an issue of great concern in developing nations. Particularly affected is India where in a National road network of approximate 33 lakh km., the National Highways account for only 2% but carry about 40% of the total road traffic [1]. Roads account for an overall 65% of freight and 80% of passenger traffic in India [1]. Total number of motor vehicles plying on these roads is an astonishing 58.86 million [2] with 30.3% households owning motorized vehicles in the urban region [3]. Adding to the woes, the number of vehicles has been growing at an average pace of 10.16% per annum over the past 5 years [1]. It is therefore of little surprise that the annual road budget for the year 2003-04 in India had been $20.078 billions [4]. However, it is estimated that an additional 57% hike in budget is essential for efficient traffic control [2]. Hence reliable, cost-effective, sustainable and replicable congestion control solutions are the need of the hour.

Besides commonly perceivable hazards like delays, traffic congestion leads to several ‘latent’ perils[5] : (a) It reduces regional economic health being a non-productive activity (b) Wasted fuel increases air pollution and hike in fuel cost. Automobile sound enhances sound pollution. (c) Wear and tear of vehicles, frequent acceleration and braking leads to repair and replacements. (d) Emergency vehicles cannot be bypassed. (e) Stressed and frustrated motorists are prone to road rage and accidents. (f) Spillover from congested main roads to secondary roads or arteries are attempted ('rat race') and this leads to further congestion and mayhem.

To model traffic dynamics, several congestion theories have been propounded. Boris Kerner proposed a three phase traffic theory. However, the most prevalent one is the fluid flow theory where congestion is linked to chaos triggering "butterfly effects". Economist Anthony Downs, in his book "Stuck in Traffic" viewed congestion in analogy to the "tragedy of the commons". The queuing theory is another proposed model to simulate traffic flow. However, none of the theories could come up with any feasible cost-effective solution to reduce congestion.

Attempts to control traffic flow have been made through cutting edge technologies, but most of them are ill-adapted to meet the demands of developing nations. The main design goal should be to develop low-cost, sustainable solutions to high congestion with considerable precision. A common solution is through CCTVs installed at congestion prone zones to disseminate current traffic information. This solution is however limited, not holistic, costly and time-consuming. Another attempt has been made with moving vehicle sensor trackers like the CM-30 Noptel Laser Distance sensor [6] which is again not suitable from an Indian perspective due to cost factors. A recent plan developed by the Bangalore Police is the Rs. 350 crore B-TRAC 2010 [7] which will estimate the number of mobile users currently on the road through cellular operators and ask the police to act accordingly. The mobile users can also ask for traffic information through SMSes sent to the service provider. The system however is not automated and has some inherent flaw as the number of mobile users at a place can never be equated to the congestion occurring at the place. Any mass gathering at nearby areas beyond resolution limit will result in flawed information and will make the system unreliable. This system is yet to be launched and is targeted to begin in 2010. However, this definitely serves as a strong proof of our proposition to use mobile telephony to disseminate traffic information.

Recently UC Berkley [8] has launched a project where they have used a large number of sensor motes for traffic monitoring. It will again be unsuitable in the perspective of developing nations like India because of the sensationally large number of vehicles and commuters, the sensors are likely to get damaged frequently. Thus the system though cost-effective is not suitable in the setting of heavy congestion prone regions.

The argument behind the failure of previous attempts to control congestion is that such attempts controlled congestion only after it has happened. For example, only when the CCTV detects that there is a congestion, then and then only do traffic information flow to prolong vehicle stoppage at previous signals. For a country like India where the number of vehicles far exceeds the carrying capacity this attempt is inherently sluggish. For by the time the information flows to a previous control point, a large number of vehicles have already entered into the congestion zone deteriorating the situation further. The only feasible solution to this problem can come through information-based predictive control and this is ensured through selective placement of ILDs, piezosensors and NOx sensor enabled wireless sensor node.

The organization of the paper is as follows: We begin by defining an automated traffic system and the system objectives. Then we outline our methodology of load prediction and traffic diversion. We then present the simulation results. Next we detail the benefits associated with the proposed scheme. The limitations concerning the replicability of the scheme are highlighted next. We finally conclude delineating the scopes for future improvement.

2. Automated holistic traffic management

A system is said to be automated or standalone if it can operate efficiently without the need of any individual. An automated system is said to be holistic if it is: (a) Reliable (b) Sustainable (c) Replicable (d) Scalable (e) Cost-effective (f) Robust (g) Delay tolerant and (h) provides user-end satisfaction. This work aims to design an automated holistic traffic system.

The automated system design is completed in two steps which basically forms the innovative foundation of the work:

1. Low-cost architecture for information acquisition for predictive load estimation with considerable precision
2. A predictive traffic control system using Wireless Sensor Networks, cellular networks and controlled traffic display boards.

3. Predictive load estimation

An accurate low-cost technique for information generation regarding current congestion status is necessary for an effective congestion control technique. Several traffic signal controllers have been designed in the past with an exhaustive list provided in [9] excluding the recent weigh-in-motion (WIM) method given in [10]. However most of these methods are costly with the lowest cost solution being ILD (Inductive Loop Detector) which costs around $500 for each detector. But almost all the previous methods based their operation on vehicle count which necessitates multiple ILDs as shown in Fig. 1. (Velocity based measurements using Active and Passive IR exist but they are costly). Since multiple detectors are necessary for an approximate count, it has been estimated that about 50 6ft*6ft inductive loops are necessary for proper traffic monitoring at a heavily congested junction. This raises the cost to at least $25000 per monitored junction for the ILDs alone, leaving aside the other necessary components. Another recent method is the weigh-in-motion which uses piezoelectric sensors embedded under the road to gain an approximate weight of the vehicle. An array of such piezosensors will give us an idea of the total stress at the junction from where it is possible to get an idea of the vehicle count within a ±10% deviation. However this method too controls traffic signal duration based on vehicle count and an array of such sensors may be unaffordable for developing nations.

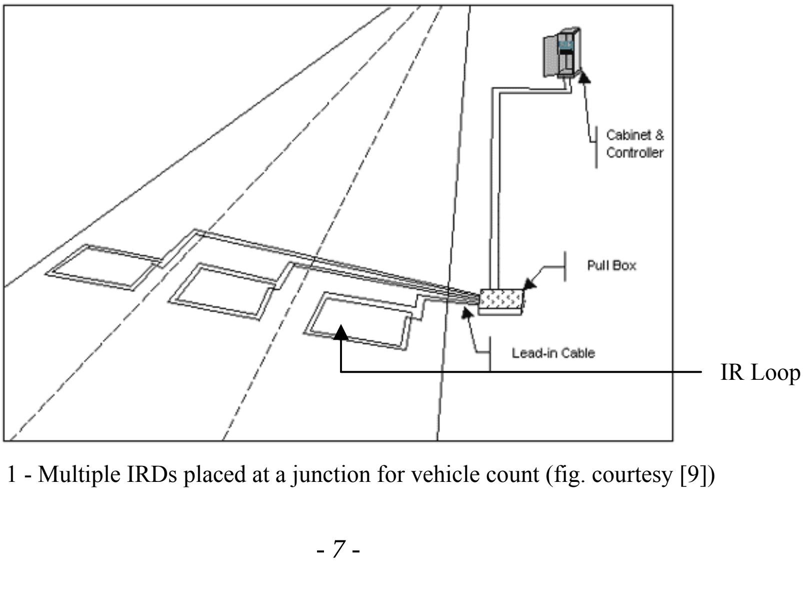

Fig. 1 - Multiple IRDs placed at a junction for vehicle count (fig. courtesy [9])

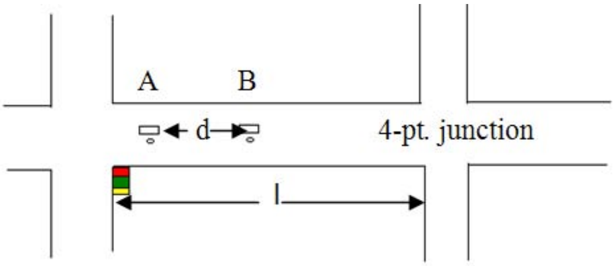

Fig. 2 - Piezosensor and IRD array for queue detection

This work radically differs from the proposition that vehicle count only provides signal control information. An estimated queue length can be equally useful for signal control. Suppose as in Fig. 2. two sets of a piezosensor and an IRD are placed a distance '*d*' apart at points A and B. Then if the stress-reading of both the piezosensor and the signature of the IRDs remain unaltered after a time't_1' then we can safely assume that there has been a vehicle queue from point A to point B. Thus just by means of two piezosensors and IRDs, a queue formation can be detected (though the exact length of the queue can not be known). This is a drastic cost reduction. By judicious selection of '*d*' and '*t*', along with the selection of a wireless sensor we can now control traffic flow. A philosophical abstraction of the system model needs to be introduced for a better perception of the intention.

3.1. System model

The traffic signal controller is analyzed in analogy with computer network theory where the moving vehicles are incoming packets and the monitored junction is a buffer which stores packets for a time '*t*' before disposing it in bursts. '*d*' is then the permissible buffer capacity after a time *t*/2, which is the first half of the time slot. After a time'*t*/2' it is checked whether the buffer mid-capacity 'd' has overflowed or not.

This is done by the piezosensor-IRD array in the practical case. If it has overflowed, then an estimate is made as by how much it has overflowed. This will be performed by the wireless sensor node. Suppose the overflow is '*k*' packets. This is to some extent analogous to carrier sense. An estimate of the buffer capacity (limit) in time'*t*' already exists. Let it be '*l*' packets. It is then obvious that if '*l-d-k*' packets scheduled for the junction be diverted in the remaining time'*t*/2' then buffer overflow can be avoided. This is analogous to traffic signal control and traffic diversion. Thus, by means of the simple principle of packet switching congestion can be controlled.

3.2. Derivation of 'd'

The distance 'd' can be defined as the tolerable limit of congestion at half of signal time. The most important part of an efficient design is a judicious selection of '*d*'. The numerical value of '*d*' is going to vary from junction to junction and will depend on signal time and the congestion history at the junction. It is evident that greater the distance '*l*' between the monitored junction and the next junction point, as in Fig. 2, greater will be the value of tolerable congestion limit '*d*'. Further, '*d*' is going to depend on the number of vehicles flowing in to the junction and the length of the queue formed by these vehicles.

Again, the distance '*l*' between two signals in a metropolis like Calcutta (a test case) varies between 300m. to 1.5 Km. So a linear dependence of '*d*' on '*l*' is going to make '*d*' too large on the higher side and a '√*l*' dependence is going to make it too small for inter-junction distance of 300m.

So a '*d*' variation of '$l^{2/3}$' is considered. The index of '*l*' will vary from city to city.

The entrance of cars in the lane being a time dependent stochastic process will follow discrete Poisson Distribution. Thus

$$d \propto l^{\frac{2}{3}}$$

$$\propto e^{-\frac{N_V}{n-1}} \frac{\left(\frac{N_V}{n-1}\right)^{\left(\frac{xd}{l_V}\right)}}{\left(\frac{xd}{l_V}\right)!} \left(\frac{l_V}{x}\right)$$

where

N_V = mean number of vehicles flowing into the lane in time '*t*/2'

$$= \frac{\sum_{i=1}^{7} n_i}{7}$$

where n_i is the total number of vehicles flowing into the lane in time '*t*/2' on the i^{th} day of the week.

n = degree of the junction from which inflow into the lane occurs. In fig. 2., a 4-point junction is illustrated. Thus *n*-1 is the number of inlets in the lane.

Considering an unbiased situation (which is true if the junction be highly busy, when the number of cars far exceeds the number of buses and autos plying on designated routes and if the number of buses and autos plying on each route be equal), the probability that a vehicle enters the lane under consideration = 1/(*n*-1). However, in most daily situations the situation is biased and an estimate of the probability can be obtained from a statistical survey as presented in Table 2 for our test case.

x = number of vehicles which can stand side by side on the lane.

l_V = mean vehicle length corresponding to the junction

$$\frac{\sum_{j=1}^{3} w_j l_{Vj}}{N}$$

where w_j denotes the weight for the j^{th} vehicle in Table 1 to be obtained from Table 2 and l_{Vj} is the length of the j^{th} vehicle obtained from Table 1. Thus

$$d = K.\ l^{\frac{2}{3}} .\ e^{-\frac{N_V}{n-1}} \frac{\left(\frac{N_V}{n-1}\right)^{\left(\frac{xd}{l_V}\right)}}{\left(\frac{xd}{l_V}\right)!} \left(\frac{l_V}{x}\right)$$

where K is a proportionality constant.

Tab. 1 - Average length of vehicles

Index j	Vehicle Category	Mean Length
1	Buses and Matadors	10m.
2	Cars and Autos	4.15m.
3	Trucks	12m.

Since l_V/x is a constant for a particular junction, we incorporate it in K. Thus

$$d = K.\ l^{\frac{2}{3}}\ .\ e^{-\frac{N_V}{n-1}} \frac{\left(\frac{N_V}{n-1}\right)^{\left(\frac{xd}{l_V}\right)}}{\left(\frac{xd}{l_V}\right)!} \quad (1)$$

After exhaustive survey, it has been found out that for Kolkata roads in order to obtain a feasible $0<d<200$m., K = 100.

3.3. Test case

The test case for implementation is chosen at Jadavpur 8B crossing which faces heavy daily traffic congestion due to Jadavpur University, 8B bus terminus, the Jadavpur rail station and two markets located close by. Besides it also lies on route to Gariahat and Tollygunge Metro Station and hence faces heavy traffic load.

Out of 710 vehicles on 20.01.08, 632 were cars and autos and 78 were buses. Thus using Table 1, l_V=4.8 m.

For Jadavpur 8B bus stand there are 3 inlets (refer Fig. 5.). Thus n-1=3. From Table 2 and 3, N_V(for 1 min.) = 79.8 and N_V(for 0.5 min.) =39.9. For 8B bus stand, x=2 and l=600m. [from Sulekha to 8B(see Fig. 5.)].

Thus from (1), the solutions of d are 88.8.m. (for 1 min.) and 52.8m. (for 0.5 mins.). Thus the estimated tolerable queue length for no congestion at 8B junction of S.C.Mallick Road is 52.8m. in 0.5 mins. and 88.8m. in 1min.

Now, if the signal time is set as 1min., the piezoelectric and ILD arrays are therefore placed the junction mouth and 52.8m. from it and the wireless sensor node is placed at (52.8+88.8)/2 or 70.8m. from the junction mouth.

The sensor node is provided with two NOx sensors since auto emissions contain significant amount of Nitrogen Oxides. Recently the EPMS project by the Japanese National Police Agency witnessed the development of a NOx sensor which can accurately trace the origin of NOx depending on its concentration within a 3% accuracy provided the origin lies within 50m as shown in Fig. 6.

It is expected that since the proposed congestion control algorithm delays vehicles for only 1 min., none of the vehicles will turn off their engines and hence an accurate estimation of queue length will be obtained.

Again since sensor nodes are highly energy constrained, the node is put to sleep mode and woken up only when the reading of the piezosensor - ILD arrays are invariant after 0.5 mins. This enhances node lifetime.

An accurate estimate of current load is thus obtained within a 2% error.

Fig. 3 - Building traffic congestion at Jadavpur (Google Earth View)

Fig. 4 - The monitored area Jadavpur-Sulekha S.C.Mallick Road

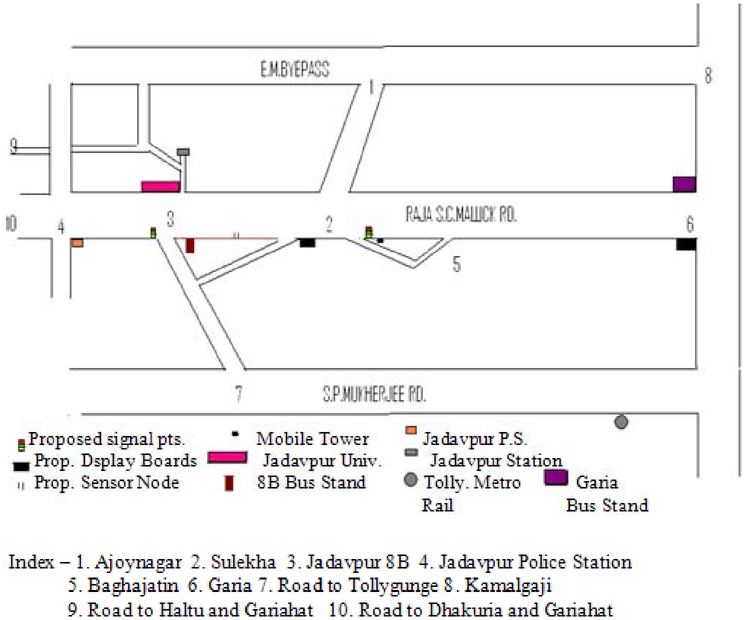

Fig. 5 - Schematic of monitored test area

3.4. Predictive diversion

Suppose, under some unfortunate situation, the piezosensor-ILD arrays yield invariant reading after 30sec. The sensor node is now aroused. Let the reading of the sensor node be s, which may both be positive or negative, depending on the direction of the accumulated queue. The sign of s can be decided by interpreting the readings of the two sensors.

Tab. 2 - Survey Statistics

Date and Time	Time duration	Total No. of vehicles	Coming from Jadavpur		Coming from Ajoynagar		Coming from Garia	
			To Ajoynagar	To Garia	To Jadavpur	To Garia	To Jadavpur	To Ajoynagar
20.01.08 7 p.m.	15 mins.	710	155	150	145	75	140	45
21.01.08 11a.m.	15 mins.	1120	231	244	208	112	240	85

Tab. 3 - Survey statistics

Date and Time	Time duration	Total No. of vehicles	Coming from Tollygunge	
			To Jadavpur P.S.	To Sulekha
21.01.08 12 noon	15 mins.	158#	80	64

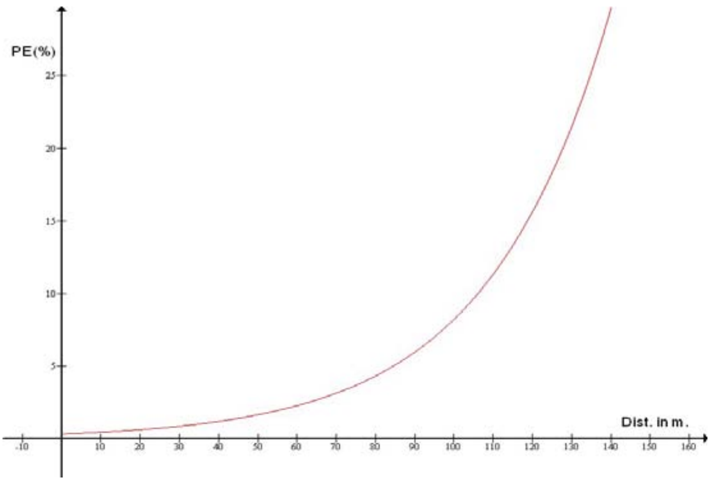

Fig. 6 - Response of NOx sensor [PE=Predictive Error]

Let s be positive towards A. For no congestion, in 0.5 mins. 52.8m. was the tolerable limit. But currently (70.8 – s)m. of queuing has occurred (refer Fig. 7). So an additional queue of (18-s)m. has accumulated during the first 30secs.

This is equivalent to an accumulation of [2(18 – *s*)/4.8] extra vehicles during the first 30secs. Suppose if s= -1.2m, then an additional 8 vehicles have entered into the lane. So in the remaining 30secs. of signaling, congestion can be controlled if at least 8 Jadavpur 8B bound vehicles are diverted from their path.

This is ensured through a three-tier structure:

1. Display board near byelane at Sulekha (refer Fig. 5) for immediate diversion.
   Display board at Garia for permanent diversion.
2. Signal control at less-queuing zone near Sulekha under emergency situations.
3. Current status information through mobile network for further diversion.

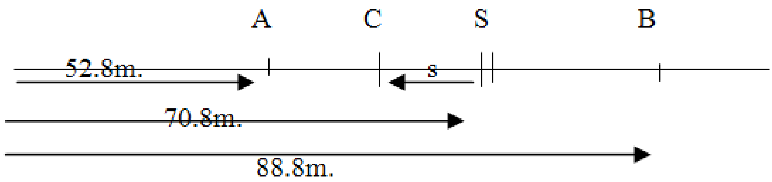

Fig. 7 - Sensor placement and reading

3.4.1. Display boards

The objective is to divert (18-s)/2.4 vehicles in the next 30secs. As an immediate effect we use the display board in front of the byelane shown in Fig.5. which directs Tollygunj bound vehicles coming from Sulekha to avail this alternative passageway.

This hopefully will solve the problem in most cases. However, this is a temporary diversion and does not in effect reduce the load handled by the 8B junction.

To effect a permanent diversion, a second display board must simultaneously flash this message at Garia (refer Fig. 5.) where the cars heading for Gariahat or E.M.Byepass via Jadavpur can redirect their path through Kamalgaji (refer Fig. 5.).

This undoubtedly will solve the problem.

3.4.2. Signal control under emergency

In cases where byelanes are not available or if in case emergency arises then we force traffic flow to stop by proper signaling in the next road intersection which in this case happens to be Sulekha which handles lesser load than Ajoynagar and does not have a traffic signal at present. The signal duration is ‘t/4’ in this case. This is effected if in any case the reading of the sensor falls below -18m.

3.4.3. Current information dissemination

To make the model sustainable and business oriented, the information of the wireless node is updated through the nearest mobile tower (see fig. 5.).

Thus the current status information – no congestion if no communication is received from the wireless node and congestion if communication is received – is now made available to the subscribers of the service provider.

People can thus send SMSes to know the current status of a junction and make knowledgeable, intelligent decisions before deciding on their route for travel.

The three tier structure almost guarantees congestion control as evidenced from the results.

4. Results

The traffic structure is simulated following the system model using the Omnet++ simulator with C++ but the results have been shown using the Graph software for simplicity of interpretation.

With the proposed model, out of the 100 runs taken, each of duration 10 mins., only in one case the congestion was found to exceed 88.8m. at any given instant of time. The maximum queue length has been plotted against the number of the run in Fig. 9 with the proposed congestion control technique.

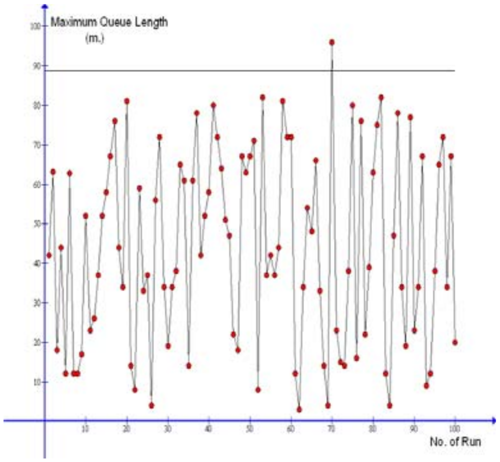

Fig. 8 - Maximum Queue Length with proposed Congestion Control

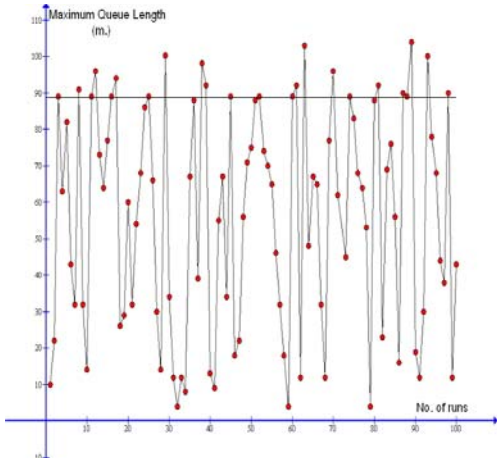

Fig. 9 - Maximum Queue Length without Congestion Control

It is easily observed from Fig. 10, that under no congestion control technique there are 27 situations in which congestion exceeds the tolerable limit of 88.8m.

A similar analysis has been carried out for the Gariahat junction (which is another congested junction of Calcutta) and has been found to yield better results with congestion control.

It may be noted that the general congestion at the signalized junctions under consideration have been estimated to be more than 1 min. which corresponds to level F (forced or breakdown flow) service according to [15].

However, with the proposed congestion control method the delay at each junction is reduced to at least 30 sec. or less which corresponds to level C (stable flow) service. For situations where the LOS (level of service) is better than C, the service remains unaltered. Thus the proposed congestion control method basically upgrades all service categories below C to a stable flow situation.

5. Benefits

5.1. Cost evaluation

The equipments necessary include:

1. 2 ILDs
2. 2 piezoelectric sensors
3. Lead-in cables
4. Pull box
5. Wireless sensor node with two NOx sensors
6. One central controller (gateway) and transmitter
7. 2 display boards
8. Extra traffic signal

The total cost is expected to be around $17500-20000 per junction which is a small fraction of the cost of flyover construction.

The scheme thus offers:

1. Considerable precision at a low cost
2. Sustainability (unlike a standalone sensor network)
3. Energy-efficiency (sensor node put to low power state)

5.2. Business orientation

Unlike flyovers or other schemes proposed earlier, the proposed model is business oriented and if mobile operators be persuaded to invest in this scheme, then the maintenance cost of the network can easily be levied from the mobile service providers. Thus it has the potential to become a low-maintenance cost congestion control proposition.

6. Limitation

Though the test cases were in Jadavpur and Gariahat, the system is replicable in any congestion prone zone provided the correct d, t, N_v and l_V are evaluated for that junction. However the system may not function optimally if several junctions following the junction being monitored are prone to heavy congestion.

7. Conclusion

The proposed solution is thus :

1. Cost-effective
2. Scalable
3. Replicable under one constraint
4. Business-oriented low maintenance cost service
5. User-oriented

The scheme is thus ideally suited for application in the scenario of developing nations where congestion control needs immediate improvement and funding for public traffic is inadequate. The scheme is equally suited for developed nations as well.

References

1. National Highway Authority of India, Retrieved from http:// www.nhai.org/roadnetwork.htm
2. World Bank, Transport-India-Highway Data, Retrieved from http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/SOUTHASIAEXT/EXTSARREGTOPTRANSPORT/0,,contentMDK:20694248~pagePK:34004173~piPK:34003707~theSitePK:579598,00.html
3. Census Report 2001, Retrieved from www.censusindia.gov.in
4. Ministry of Finance (MOF Reports), available at web.worldbank.org
5. Traffic Congestion, Wikipedia, http://en.wikipedia.org/wiki/Traffic_congestion
6. Road Traffic Technologies, Retrieved From http://www.roadtraffic-technology.com/contractors/traffic_man/initial/
7. B-TRAC 2010, www.btrac.in
8. Ergen S.C., Cheung S.Y., Varaiya P., Kavaler R., Haoui A., Wireless Sensor Networks for Traffic Monitoring, Available at www.ee.ucla.edu/~mbs/ipsn05/demo/27_SErgen.pdf
9. Freeway Management and Operations Handbook, Chapter 15, Page 1 of 3

10. Weigh-in-Motion Handbooks, Centre for Transportation Research and Education (CTRE), Iowa State University, http://www.ctre.iastate.edu/Research/wim_pdf/index.htm
11. Auto Emissions: An overview, US Environmental Protection Agency, Office of Mobile Sources
12. EPMS Control and a NOx sensor for Traffic control systems, In Proceedings of IEEE International Conference on Intelligent Transportation Systems, pp. 645-648,1999.
13. Japanese National Police Agency (EPMS Project), http://www.npa.go.jp/english/
14. Remote Emission Sensing System with Improved NOx Detection, European Patent EP1137925
15. Highway Capacity Manual 2000, http://onlinepubs.trb.org/Onlinepubs/trnews/rpo/rpo.trn129.pdf