DESIGN OF TRAFFIC SIGNALS AT URBAN INTERSECTIONS – A RATIONAL APPROACH

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ABSTRACT

In the process of design of traffic signals, it is necessary to consider the requirements of different road user groups. An assessment framework is suggested considering the requirements of different road user groups. Various methodologies traditionally used for design of traffic signals have been reviewed in the light of the proposed assessment framework. It has been shown that almost all the traditional methods of signal designs are biased towards minimizing the delay for only motorized vehicles. A first step towards the equalization of utilization has been attempted by incorporating the requirements of all user groups into an optimization function considering the delay. However, further works are required to have a more refined theoretical formulation satisfying the requirements of all road users in a realistic manner.

INTRODUCTION AND MOTIVATION

Urban area traffic congestion is a major concern to transportation professionals. Urban road network consists of large number of signalised intersections and these intersections are potential sources of bottleneck in urban network. Converting at-grade signalised intersections to grade separated intersections is one of the approaches for mitigation of congestion in urban road network. However, it is practically impossible to avoid at grade intersections considering financial and physical constraints as well as aspects of townscape and urban development. Traffic control at urban intersections through proper design of signals is therefore, a crucial step for mitigation of congestion in urban road network. It is also a complex task as urban intersections and road space is used not only by motorized traffic but also by non-motorized transport modes and pedestrians. Most of the modern traffic systems are designed largely from car-users perspective. There has been a lack of coherent planning of route networks for pedestrians and cyclists. In expanding suburban areas, increased traffic on narrow roads make the sharing of roadways by pedestrians, bicycles, and motorists frustrating and hazardous for all road users. The right to travel is one of the most highly valued rights in the civilized world. Therefore, access to employment,

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goods, and services must be protected for all persons using public ways. Another serious problem is that detrimental air pollution due to congested traffic flow has reached to a critical level in many cities. Road users and residents near intersections are dangerously exposed to hazardous components of exhaust pollutants.

The reduction of air and noise pollution levels is a prime requisite for sustainable developments." Liberty for All"- Universal Access is the ability of all citizens to reach every destinations served by public road system. Universal Access is not limited to access by persons using automobiles. Travel by bicycling, walking, or wheelchair to every destination should be accommodated in order to achieve transportation equity, maximize independence, and improve community liveability. Appropriate design and regulation of the transportation system should ensure that all users have reasonable access to those destinations located within the acceptable range of travel time and modes available to them.

OBJECTIVE AND SCOPE

The broad objective of the present paper is to develop a rational approach for the design of isolated signals for urban road network by considering the requirements of different road users. An attempt is made to understand and include the requirements of motorized modes, non-motorized modes and pedestrians in the process of designing traffic signals. For many years the primary aim of Urban Traffic Control Systems had been to minimize total delay for motorized traffic. But design of signals and traffic control systems should play a much wider role for (i) Reducing the impact on air quality, (ii) Providing better and safer facilities for pedestrians, cyclists and other vulnerable road users, (iii) Improving priority for public transport, and (iv) Influencing traveller behaviour, in particular modal choice, route choice and time at which journeys are made.

In order to achieve the above-mentioned objectives, an assessment framework is prepared with an exhaustive list of requirements of all road users for a good urban traffic control system. On the basis of the assessment framework, the performance of traffic signals is judged. Besides the requirements of road users this assessment framework considers various parameters for designing traffic signals, and the criteria or Measure of Performance (MOP) for evaluating how far the requirements are satisfied by the system. Traditional approaches for optimisation of traffic signals are reviewed critically in the light of the assessment framework. A simple theoretical formulation with composite Measure of Performance is then suggested for improving the rationality of signal design.

REQUIREMENTS OF DIFFERENT USER GROUPS

The different road user groups considered in the present work are (i) Pedestrians, (ii) Bicycles, (iii) Motorised vehicle, (iv) Public transport, and (v) Emergency vehicles. The general requirements of different road user groups for a good urban traffic control system include (i) Universal Access to Destinations, (ii) Equal Rights of Use, (iii) Integration of Modes, (iv) Uniformity and Simplicity, (v) Accessible Surfaces, (vi) Crossable Roadways, and (vii) Appropriate Space for Use. Inhabitants and society are also affected by the traffic control system and thus, their requirements should also be considered.

Pedestrians

The safety and convenience of pedestrian travel is an important factor. Pedestrians travelling to important destinations must cross streets and driveways used by vehicles. Unfortunately, many traffic signals at wide intersections do not provide enough time for pedestrians to complete the crossing of street before conflicting traffic movements begin. Especially at wide intersections, emphasis should be given on the provision of appropriate green time for pedestrians in combination with sufficient intergreen time to allow the clearing of the intersection. Pedestrians should be also protected from the hazardous effects of air and noise pollution due to traffic. The major requirements of pedestrians are as follows.

- Lesser conflicts with other modes
- More safety
- More convenience and less interruptions
- More eco-friendly environment

Cyclists

The needs of cyclists may vary. Commuter cyclists may require a quick journey to their place of work or study. The utility cyclists may require a pleasant and comfortable journey. The leisure cyclists are primarily interested in facilities which by-pass large urban areas. A common desire for all cyclists is safe environment for travelling. Like motorised road users cyclists desire minimum delay to their journeys, but they may be even more sensitive to stops, because of the physical effort required to regain the momentum lost. The general requirements of cyclists are as follows.

- Lesser conflicts with motorized and pedestrian traffic
- More safety
- More convenience and less interruptions
- More eco-friendly environment

Motorists

Some important safety measures may effect reductions in motor vehicle speed, which will not be appreciated by motorists who are accustomed to travelling long distances in a shorter time. On very wide multilane suburban roads, adding adequate pedestrian clearance time to traffic signals may increase delays for motorists or decrease roadway capacity. The requirements of motorists are as follows.

- More convenience and less interruptions
- Lesser fuel consumption
- More driving comfort and segregation from non-motorized traffic
- More safety

Public transport

Public transportation system has a vital role to play for mitigation of congestion on urban road networks. Priority to public transport can be achieved by providing separate infrastructure such as bus lanes. Using Intelligent Transportation Systems (ITS), buses or trams can be detected on the approach to signalized intersections and given extended green phases to enable them to pass through with minimum delay. This improves the reliability of public transport services in areas suffering from habitual traffic congestion. It also encourages a modal shift from private to public transport as well as reduces overall traffic delays through selective priority at signals, which in turn reduces emissions. The requirements of public transport are as follows.

- More convenience and less interruptions
- More safety
- More reliability of service

Emergency vehicles

The requirements of emergency vehicles are as follows.

- Less interruptions and faster movement
- More safety
- More reliability

Inhabitants and society

People residing by the side of the roads and the society as a whole, also have some requirements on the urban traffic control system which should be considered while designing and maintaining the urban traffic control system. The requirements of inhabitants and society are as follows.

- More eco-friendly environment
- More efficiency in public and commercial transportation
- More safety
- Lesser damage on buildings

DESIGN PARAMETERS FOR TRAFFIC SIGNALS

There exist a variety of characteristics that contain input and output parameters used in the design process of traffic signals. They can be grouped under three sub headings: Intersection Geometry, Traffic Characteristics and Signal Parameters.

a) Intersection Geometry: These include Number of approaches and angles between them, Type of intersection (staggered, angular, etc.), Approach width, Number of lanes in each approach, Number of turning lanes (exclusive left turn or right turn lanes), Turning radius, Gradient of approaches, Median and public transport routes (if any), Width of footpath, Length of storage bay, LT/RT lanes, Bus stop, parking, petrol pump, Pedestrians and cyclists path of travel, Pedestrian waiting area, Visibility, etc.

b) Traffic Characteristics: These include Arrival flow rate with type of vehicles, Percent right turn, straight, left turn vehicles; Heavy vehicles, percent through buses, PHF (peak hour factor) and load factor, Headway distribution of arrival, Approach speed and acceleration and deceleration, Time required for last vehicle at the end of green phase to cross the intersection, Public transport schedule, Volume of pedestrian traffic, Volume of bicycle traffic, etc.

c) Signal Parameters: These include Control strategy (pretimed/actuated), Number of phases with phase plan, Intergreen times, Signal timing of red, amber and green for all user groups, etc.

Criteria to assess or evaluate traffic signals (mop)

The following measures of performance may be considered.

- Separate green time for pedestrians and cyclists (Yes/No)
- Stopped and overall delay for different user groups
- Air pollution level
- Noise Pollution level
- Queue length
- Accident rates involving various user groups
- Variation in total delay

ALLOCATION OF REQUIREMENTS TO THE CRITERIA

Measure of Performance may be used to judge how good the requirements of different users are considered in the process. So there must be a one to one correspondence relation between the requirements and the selected criteria. Also worth mentioning at this stage is that the criteria selected should be appropriate to the given situation. Table-1 shows MOPs that may be considered to satisfy the requirements of different road users.

Table 1. Requirements of Various User Groups and Measure of Performance

Road User Group	Requirement	Measure of Performance (MOP)
Pedestrians	Conflicts with other modes	Separate green time for movement of pedestrians only (Yes/No)
	Safety	Accident Rate involving pedestrians
	Convenience and Interruptions	Stopped as well as total delay for pedestrians
	Eco-friendly environment	Noise and Air pollution levels at or near intersection
Cyclists	Conflicts with motorized and pedestrian traffic	Separate green time for movement of cyclists only (Yes/No)
	Safety	Accident rate involving cyclists
	Convenience and Interruptions	Stopped as well as total delay for cyclists
	Eco-friendly environment	Noise and Air pollution levels at or near intersection
Motorists	Convenience and Interruptions	Stopped delay, total delay and queue length for motorists
	Fuel consumption	No. of stops for motorists
	Driving comfort and segregation	Separate green time for movement of pedestrians and cyclists (Yes/No)
	Safety	Accident rate involving motorists
Public Transport	Convenience and Interruptions	Stopped delay, total delay and queue length for public transport vehicles

	Safety	Accident rate involving public transport
	Reliability of service	Variation in total delay for public transport vehicles to clear intersection
Emergency Vehicles	Interruptions and movement	Total delay for emergency vehicles
	Safety	Accident rate involving emergency vehicles
	Reliability	Variation in total delay for emergency vehicles to clear intersection
Inhabitants and society	Eco-friendly environment	Noise and Air pollution levels at or near intersection
	Efficiency in transportation	Average delay and queue length
	Safety	Overall accident rate
	Damage on buildings	Level of Air pollutants causing damage to buildings

Present state of art – A critical review

A detailed review of the existing procedures of traffic signal design reveals that that most of the methodologies focus on the requirements of the motorists, and the requirements of other road users is not considered adequately in the process of designing signals (refer to Table-2). The review is carried out in the light of the assessment framework prepared and the lacunas of the current methods are considered while developing the proposed theoretical formulation.

Table 2. Measure of Performance in Traditional Approaches

Approach	Measure of Performance (MOP)
HCM 2000	Delay to motorists- uniform, residual demand and incremental delay
RiLSA	Delay to vehicles, bus and tram, pedestrians and cyclists
TEXAS A & M method	Average delay per vehicle
ALLSOP method	Average delay per vehicle
British TRRL method	Total delay to vehicles
ARC method	Average delay to vehicles
SCOOT	Delay per vehicle and congestion
MOVA	Throughput of traffic
UTOPIA-SPOT	Mean delay, No. of vehicle stops, queue length
MOTION	Waiting time, No. of vehicle stops, maximum queue length
PRODYN	Total time spent in network, fuel consumption
HCS,SimTraffic,CORSIM, PASSER,SYNCHRO, SIDRA, TRANSYT	Delay to motorists, stops, queue length, average speed, fuel consumption, throughput, speed progression, capacity and saturation

THEORETICAL FORMULATION

An attempt has been made to accommodate the requirements of pedestrians, cyclists, motorists and public transportation on an urban traffic control system. As an example, the delay to all road user groups has been chosen for developing an objective function. Further consideration of other criteria may be needed.

Assumptions

The following assumptions are made for the theoretical formulation presented here.

- Uniform arrival of cars from all approaches and all the cars are of the same size.
- Only stopped delay is considered.
- Only through movements considered.
- Arrival rate $(x) \leq$ Number of lanes (n).
- No acceleration and deceleration delays.
- Velocity of shock wave is fixed.
- Uniform arrival rate of pedestrian and bicyclists from all approaches.
- Fixed schedule for public transport through the signal.
- Four legged intersection with simple two-phase signal timing and all red phase =0.

Variables or Measure of Performance

The following variables or Measure of Performance are considered in the present work.

- Vehicular Delay is a measure of emission and fuel consumption.
- Pedestrian Delay is a measure of utilization.
- Bicyclists' Delay is a measure of utilization.
- Public Transport Delay is a measure of emission, fuel consumption and utilization.

Objective Function

$$\text{Minimize } Z = \sum_{n=1}^{x} \sum_{i=1}^{4} W_{i_n} D_{i_n} \tag{1}$$

Where, Z is the disutility factor.

i = road users starting from pedestrians, cyclists, motorists and public transport.

W_{i_n} = Weightage given to i^{th} road user in the nth approach according to priority.

D_{i_n} = Delay to i^{th} road user in the nth approach.

Constraints

The constraints for the objective function are as follows:

- Maximum Delay d ≤ Specified Value (dependent on road users and situation)
- Minimum Green Time = pedestrian clearance time for crossing + initial interval for pedestrian to start crossing – Amber time.
- Minimum Red time = pedestrian clearance time for crossing + initial interval for pedestrian to start crossing = minimum Green time + Amber time.
- Amount of CO, SO_2, NO_x, HC, etc. d ≤ Threshold Value.
- Maximum speed < Value specified.
- Amber time = $t + \frac{V}{(2a) \pm (64.4g)} + \frac{W + L}{V}$ (2)

Where, t = perception/reaction time for drivers in sec.
V = approach speed in feet per sec.
a = deceleration rate in feet per sec.^{2}
W = width of intersection in feet.
L = length of vehicle in feet.
g = approach grade, percent of grade divided by 100, add for upgrade.

Delay to vehicles

The stopped delay for vehicles from all directions is calculated by the following equation:

$$D(V) = xR_1 + x(R_1 - 1) + x(R_1 - 2) + ... + x(R_1 - R_1) + (L/v)x + (2L/v)x + (3L/v)x + ... + .(R_1 L/v)x + xG_1 + x(G_1 - 1) + x(G_1 - 2) + ...x(G_1 - G_1) + (L/v)x + (2L/v)x + (3L/v)x + ...(G_1 L/v)x \quad (3)$$

and for zero residual queue length:

$$(R_1 L/v) + (R_1 L/V_J) < G_1 \quad (4)$$

Where, x = Uniform arrival rate of vehicles in veh. per sec.
R_1 = Red interval in the cycle length in sec.
G_1 = Green interval in the cycle length in sec.
$C = G_1 + R_1 + A_1$ = cycle length in sec.
L = Length of a vehicle in mt.
v = Velocity of the shock wave in mt. per sec.
V_J = Velocity of vehicles in the release condition in mt. per sec.

Delay to pedestrians and bicyclists

$$D(p,b) = \{\frac{q}{2} G_1 (G_1 + 1) * 4\} + \{\frac{q}{2} R_1 (R_1 + 1) * 4\} \quad (5)$$

Where, q = uniform arrival rate of pedestrian and bicyclists from all eight directions.

Delay to Public Transport:

D (PT) = £ (arrival rate of bus or tram)*(R_1or G_1- time of arrival) (6)

CLOSURE

A rational approach for the design of traffic signals has been explored in the present paper by considering the requirements of different road user groups including pedestrians, bicycles, motorised vehicles, public transport and emergency vehicles. An assessment framework is suggested based on requirements of different user groups. The assessment framework is useful to judge the adequacy of a traffic signal design process. Various methodologies traditionally used for design of traffic signals are reviewed in the light of the proposed assessment framework. It is shown that almost all the traditional methods of signal designs are biased towards minimizing the delay for only motorized vehicles. In this study, a first step towards the equalization of utilization has been attempted by incorporating the requirements of all user groups into an optimization function considering the delay. However, further works are required to have a more refined theoretical formulation satisfying the requirements of all road users, the inhabitants and the society in a realistic manner.

REFERENCES

1. Gartner, N.H., and Wilson, N.H.M. (1987). "Transportation and Traffic Theory", Elsevier.Gartner, N.H., and Improta, G. (1995). "Urban Traffic Networks- dynamic flow modeling and control", Springer –Verlag.
2. Highway Capacity Manual, (2000). SR209, Fourth Edition, TRB, Washington D.C.
3. Institute for Transport Studies, (2000). "The potential for incorporating considerations of Bicycle traffic in Urban Traffic Management and Control systems", UTMC24, Copy1.
4. Khisty, C.J., and Lall, B.K. (2002). "Transportation Engineering", Third Edition, Prentice Hall of India.
5. Niittymäki, J. and Sihvola, T. (2001). "Potential of energy and environment savings in different infrastructural design", Advances in Transportation Studies, Section B1.
6. Oscar Faber, (2000). "First Project Report- Review of ITS Applications, Evaluation Procedures and Benefits", UTMC05a, Performance Indicators.
7. Papacostas, C.S., and Prevedouros, P.D. (2002). "Transportation Engineering and Planning", Third Edition, Prentice Hall of India.
8. RiLSA, (1992). Guidelines for traffic signals, Germany.