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Model Based Control of Mixed Traffic Based on Area Occupancy ⋆

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Abstract: Regulation of heterogeneous traffic is a challenging task on urban roads, particularly those where traffic congestion is routinely encountered. In this paper, a model based traffic signal control scheme via state feedback controller is presented. An original contribution of this study is the use of area occupancy as the measurement variable, which is apt for characterising heterogeneous and lane less traffic. An adaptive Kalman filter is used to estimate traffic density. The developed control scheme was implemented on a road stretch simulated in VISSIM, a commercial microscopic traffic simulation software, and interfaced with MATLAB using VISSIM COM interface. The implementation was shown to satisfy the objective of maintaining the desired density in the study stretch which demonstrated the effectiveness of the developed control scheme.

Keywords: Time varying systems, Road traffic, Kalman filters, Traffic control, State feedback,

1. INTRODUCTION

Traffic signals are the most practical means to regulate and control road traffic in situations where scope of expansion of existing infrastructure is limited. The effectiveness of traffic signals depends on factors such as green time allocation and coordination with adjacent signals. Since the traffic conditions vary with time, an ideal signal must be responsive to real-time changes in the same. With the exponential surge in traffic, currently installed signals are often unable to comply with these factors and subsequently, signals themselves transform into recurrent sources of traffic congestion. Hence, there exists a need for more effective control of traffic signals.

Control strategies for traffic signal are classified on the basis of the time of the day as fixed or real time, number of intersections being single or multiple, and traffic conditions, whether under saturated or over-saturated [Papageorgiou et al. (2003)]. Various adaptive traffic signal control systems have been developed over the years that take into consideration the real time traffic fluctuations. The split-cycle offset optimisation technique (SCOOT) developed by Robertson and Bretherton (1991), the Sydney coordinated adaptive traffic system (SCATS) by Sims and Dobinson (1980), and the regional hierarchical optimised distributed effective system (RHODES) by Mirchandani and Head (2001) are some of the popular adaptive control systems in use globally across various countries. The implementation of these systems has been effective in reducing the average travel times by 10 % to 40 % [Studer et al. (2015)]. SCOOT and SCATS, however may fall short during rapidly changing traffic conditions and RHODES may not be suitable for central network-wide applications because of the complex algorithms involved. Due to modelling limitations, their efficiency in over-saturated conditions has not been much evaluated [Samadi et al. (2012)].

Traffic flow models can be either microscopic or macroscopic, based on the level of detailing. Microscopic models describe the precise individual details pertaining to traffic like driver-driver and driver-road interactions, and traffic characteristics such as time and space headways. Macroscopic models on the other hand represent the traffic stream in terms of representative speed, flow and density. Traffic on Indian roads are predominantly heterogeneous with the vehicle composition on the limited available infrastructure constituted by a mixture of two wheelers, three wheelers, and four wheelers. Lack of lane discipline even on multi-lane roads is rather commonplace. Additional factors like varying vehicle speeds, frequent intersections and merging traffic from side roads also affect traffic response. Studies on heterogeneous traffic in Indian conditions have mostly been done using microscopic models [Mallikarjuna and Rao (2009); Metkari et al. (2013)]. However, extensive data collection and estimation with associated computational expense may limit their feasibility in real-time situations. Hence, the present study was aimed to develop a macroscopic model based traffic control scheme for heterogeneous traffic under over-saturated conditions.

Some of the recent studies that have explored model based control schemes in the context of urban traffic are mentioned below. Zhou et al. (2016) proposed a multi-level hierarchical control scheme for heterogeneous traffic with controls for traffic demand and signal optimisation. A hier-

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archical design was also presented by Hao et al. (2018a,b) where current state estimate was used for timing of signal lights at a single intersection followed by coordination between adjacent intersections based on the traffic density. Dynamic optimisation of multiple objectives for predictive network signal control was proposed by Li and Sun (2019). It was observed that dynamic control in different situations led to optimal traffic performance. However, there is a scarcity of similar studies in the Indian context. In one such reported study, Verghese et al. (2016) developed a state feedback controller under over-saturated conditions. The employed model was based on conservation equation and an empirical relation, which was site specific.

Motivated by the above, this study proposes the use of a more generic model based control scheme. Traffic in the study stretch was characterised by density, a good measure of congestion [Manual-HCM (2010)]. While considering mixed traffic conditions (heterogeneous and lane less traffic), a variable sensitive to corresponding dynamic changes is more suited. Hence, the proposed system considered area occupancy as measurement, since the measure of the vehicle area may be more appropriate for heterogeneous traffic [Khan and Maini (1999)]. Area occupancy takes into consideration the varying vehicle dimensions and is therefore capable of capturing lane indiscipline and heterogeneity [Mallikarjuna and Rao (2006); Arasan and Dhivya (2008)].

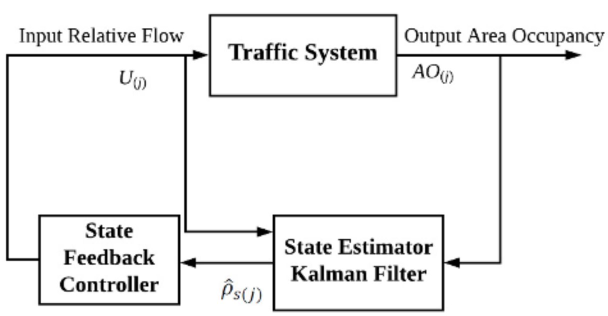

Fig. 1. Schematic representation of the control scheme

Figure 1 shows the schematic of the control scheme. The measurement of density is demanding, hence estimation using an adaptive Kalman filter was done with relative flow and area occupancy as input. The estimated density was then used to generate the control input. The control objective of maintaining density at a desired value was attained using a full state feedback controller. Relative flow, which is the control input, was converted into green time using the basic concepts of saturation flow and capacity. Signal control regulated the amount of traffic entering and exiting the section so as to maintain the desired density in the study stretch. Due to the practical limitations in implementation, the road stretch under study was simulated using VISSIM, a traffic simulator. VISSIM COM (Component Object Model) interface, which provides inter-process communication between software was used to realise the developed scheme. The data processing and online estimation was done using MATLAB, which was interfaced with VISSIM.

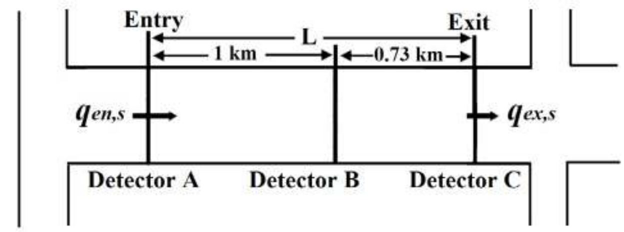

Fig. 2. Schematic of the study stretch

2. MODEL FORMULATION

The traffic system was modelled using a single state linear time varying model and expressed in state space form. The selected road stretch was an urban arterial road along Rajiv Gandhi Salai in the city of Chennai, India. A mid-block of length L, 1.73 km bounded by two signalised intersections with three foot over bridges named A, B, and C as shown in Fig. 2 was considered for the study. Out of six lanes, the study considered three lanes in one direction, each lane having a width of 3.5 m.

The model was a non-continuum macroscopic model with density describing the traffic inside the section. The principle of conservation of vehicle was applied to obtain the state equation. The arrival rate of vehicles to the section was taken to be $q_{en,s(j,j+1)}$ and the departure rate was taken to be $q_{ex,s(j,j+1)}$ in the time interval, h between the j^{th} and $(j+1)^{th}$ instants of time. At j^{th} instant of time, the count of vehicle inside the section be $N_{s(j)}$. Then by vehicle conservation, at $(j+1)^{th}$ instant of time the count of vehicles inside the section can be given as

$$N_{s(j+1)} = N_{s(j)} + h(q_{en,s(j,j+1)} - q_{ex,s(j,j+1)}), \quad (1)$$

where $(q_{en,s(j,j+1)} - q_{ex,s(j,j+1)})$ is the relative flow, $q_{rel,s(j,j+1)}$. The density $\rho_{s(j+1)}$ at $(j+1)^{th}$ time instant, can be derived from equation (1) as

$$\rho_{s(j+1)} = \rho_{s(j)} + \frac{h}{L}(q_{en,s(j,j+1)} - q_{ex,s(j,j+1)}), \quad (2)$$

which forms the state equation.

The output equation was obtained from the concept of area occupancy, a non-dimensional variable. Over time, this measurement captures heterogeneity and lane indiscipline by taking into account the varying vehicle dimension [Mallikarjuna and Rao (2006)]. The percent area occupancy, expressed as the proportion of time the chosen section of the road is occupied by vehicles [Arasan and Dhivya (2008)], is given by

$$AO_{(j)} = \frac{\sum_{k=0}^{N_d} a_k t_{k(j)}}{Ah} 100, \quad (3)$$

where $t_{k(j)}$ is the time duration for which the detection zone is occupied by the k^{th} vehicle, a_k is the area of the detection zone occupied by the k^{th} vehicle, N_d is the number of vehicles passing over the detector in the interval h, and A is the area of the detection zone.

From the fundamental relation between speed, flow and density and the definition of the space mean speed, density-area occupancy relation can be derived as

$$AO_{(j)} = \frac{\sum_{k=0}^{N_d} a_k t_{k(j)}}{AN_d} U_{sms(j)} 100 \rho_{s(j)}. \quad (4)$$

The state space model for the traffic under study was represented by equations (2) and (4).

3. ESTIMATION SCHEME

The model based estimation scheme Kalman filter [Kalman (1960)] was used for the density estimation. This recursive filter considers the stochastic nature of the process disturbance and measurement noise. From equations (2) and (4), the state equation and output equation with the inclusion of the stochastic nature of traffic in general, can be expressed as

$$x_{(j+1)} = ax_{(j)} + bu_{(j)} + w_{(j)}, \tag{5}$$

$$z_{(j)} = c_{(j)}x_{(j)} + v_{j)}, \tag{6}$$

where $x_{(j)}$ represents the state variable, $u_{(j)}$, the input variable and $z_{(j)}$, the output variable. The variables $w_{(j)}$ and $v_{(j)}$ were considered as normally distributed zero mean, uncorrelated white noise sequences with finite co-variance q and r respectively. The trust in the process model is high since the formulation was done from the principle of vehicle conservation. As the traffic condition on the road can vary due to recurring and non recurring reasons, the measurement can be expected to be noisy. Some inaccuracy in the measurement model is also expected. Hence the filter is made adaptive by fixing q and varying r. In the proposed adaptive Kalman filter algorithm, the state prediction and state co-variance prediction are

$$\hat{x}^-_{(j+1)} = a\hat{x}^+_{(j)} + bu_{(j)}, \tag{7}$$

$$p^-_{(j+1)} = a\hat{p}^+_{(j)}a + q, \tag{8}$$

where $\hat{x}^+_{(j)}$ and $p^+_{(j)}$ denote the updated estimate of the state and estimation error variance at the $(j)^{th}$ instant respectively and $\hat{x}^-_{(j+1)}$ and $p^-_{(j+1)}$ denote the predicted estimate of the state variables and estimation error variance at the $(j+1)^{th}$ instant of time respectively. The statistical properties of measurement noise were calculated from the residue of the difference between the actual measurement and the predicted value for each interval, and is given by

$$res_{(j+1)} = [y_{(j+1)} - c_{(j+1)}\hat{x}^-_{(j+1)}]. \tag{9}$$

The simple mean and variance of this residue was calculated to obtain the quantity $\bar{v}_{(j+1)}$ and the measurement covariance $r_{(j+1)}$. The Kalman filter update steps are as follows:

$$K_{(j+1)} = p^-_{(j+1)}c_{(j+1)}\left[c_{(j+1)}p^-_{(j+1)}c_{(j+1)} + r_{(j+1)}\right]^{-1}, \tag{10}$$

$$\hat{x}^+_{(j+1)} = \hat{x}^-_{(j+1)} + K_{(j+1))}[z_{(j+1)} - c_{(j+1)}\hat{x}^-_{(j+1)} - \bar{v}_{(j+1)}], \tag{11}$$

$$p^+_{(j+1)} = [1 - K_{(j+1)}c_{(j+1)}]p^-_{(j+1)}, \tag{12}$$

where $K_{(j+1)}$ is the Kalman gain, which represents the updating weight between the measurements and the prediction from the system dynamic model. This estimation scheme was implemented with the developed model represented in equations (2) and (4).

4. CONTROLLER DESIGN

The objective of the control scheme is to maintain an optimum density in the selected study stretch. As the proposed linear discrete system was found to be completely controllable and observable, a full state feedback controller was designed. Considering the desired density to be ρ_d, the error $e_{(j)}$ at j^{th} time instant is

$$e_{(j)} = \rho_{s(j)} - \rho_d. \tag{13}$$

The error dynamics can be expressed as

$$e_{(j+1)} = e_{(j)} + \frac{h}{L}(q_{en,s(j,j+1)} - q_{ex,s(j,j+1)}). \tag{14}$$

In state feedback control, the control action places the closed-loop pole at the desired location to achieve the expected response. The control equation is taken as $U_{(j)} = K_s e_{(j)}$, where $U_{(j)}$ is the control input and K_s is the feedback gain. For the system to be asymptotically stable, the closed loop pole located at $z = 1 + \frac{h}{L}K_s$, should lie within the unit circle. It was found that the corresponding range of K_s was (-124, 0). The value was selected for K_s as -60 by tuning in this range. The estimated density from adaptive Kalman filtering technique was used in the control scheme. To evaluate the performance of the developed model-based control scheme, controller along with the estimator was simulated.

5. IMPLEMENTATION OF THE CONTROL SCHEME

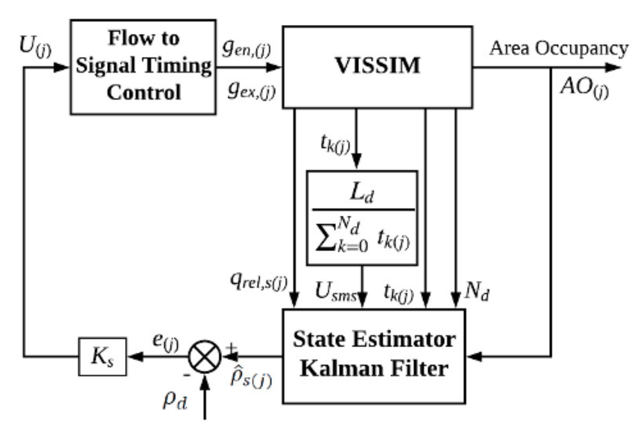

Fig. 3. Implementation of controller with estimator

Figure 3 shows the schematic for the implementation of the controller with estimator. Since the real time implementation of controllers on the actual road stretch is challenging, the performance of the control scheme can be evaluated by implementing it in a traffic simulation software, VISSIM [PTV (2011)]. The default parameters of this software have been originally developed for the lane disciplined and homogeneous European traffic conditions. However, it offers the option of setting the parameters to the heterogeneous and lane less traffic conditions observed in India. The calibrated parameters by Anand et al. (2014) were used in this study. The network based on the real geometry was constructed through graphical user interface (GUI) and traffic parameters were reproduced using VISSIM.

The control problem to maintain the desired density was achieved by regulating the input, relative flow. To achieve this, the control input $q_{rel,s(j+1)}$ is converted to green times of entry and exit traffic signals using the algorithm shown in Fig. 4. The variables $g_{en,s(j+1)}$, $g_{ex,s(j+1)}$ and $g_{rel,s(j+1)}$ represent the entry green time, exit green time

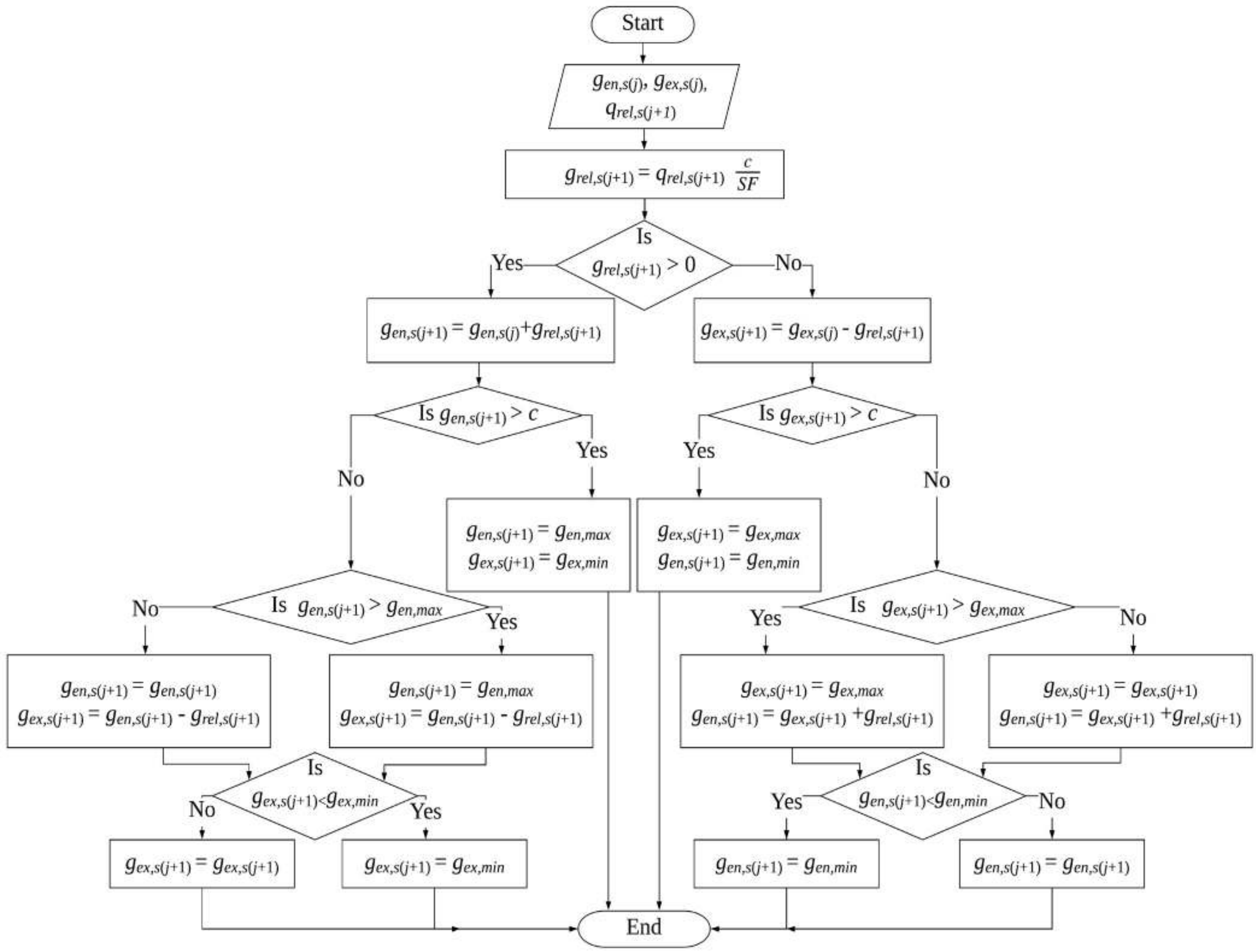

Fig. 4. Relative flow to green time algorithm

and relative green time between entry and exit at $(j+1)^{th}$ cycle respectively. The maximum green time for entry and exit was denoted by $g_{en,max}$ and $g_{ex,max}$. The entry and exit minimum green time was denoted as $g_{en,min}$ and $g_{ex,min}$ respectively. The conversion algorithm takes the j^{th} cycle green time $g_{en,s(j)}$, $g_{ex,s(j)}$ and the control input $q_{rel,s(j+1)}$ as inputs. The relative green $g_{rel,s(j+1)}$ was expressed as a function of saturation flow SF, signal cycle time c and $q_{rel,s(j+1)}$ as

$$g_{rel,s(j+1)} = q_{rel,s(j+1)} \frac{c}{SF}. \quad (15)$$

The basic concept of green time allocation is

$$g_{rel,s(j+1)} = g_{en,s(j+1)} - g_{ex,s(j+1)}. \quad (16)$$

If the value of $g_{rel,s(j+1)}$ is postive, green entry will be updated as

$$g_{en,s(j+1)} = g_{en,s(j)} + g_{rel,s(j+1)}. \quad (17)$$

If the updated green entry exceeds signal cycle time, $g_{en,s(j+1)}$ will be taken as $g_{en,max}$ and $g_{ex,s(j+1)}$ will be taken as $g_{ex,min}$. On the other hand, if the updated green entry is greater than $g_{en,max}$ and less than cycle time, $g_{en,s(j+1)}$ will be taken as $g_{en,max}$ and if it is less than $g_{en,max}$, updated green entry will be retained. In both cases, the $g_{ex,s(j+1)}$ will be allocated using equation (16) and the minimum green condition is checked.

If the $g_{rel,s(j+1)}$ is negative, the green exit will be updated as

$$g_{ex,s(j+1)} = g_{ex,s(j)} - g_{rel,s(j+1)}. \quad (18)$$

Similar procedure was followed for allocation of the green entry and green exit.

Accordingly, the parameter of the signal control needs to be dynamically changed for every cycle. The online implementation of the estimation scheme and conversion of control input to green times also need to be done. These were achieved by VISSIM COM interface [Tettamanti and Varga (2012)], which provides inter-process communication between software. The VISSIM COM interface defines a hierarchical model in which the functions and parameters of the simulation originally provided by the GUI can be adjusted through MATLAB. Once the study stretch was generated in GUI with the road geometry, vehicle input, signal heads and detectors, COM client was created. The simulation was implemented using the COM program in MATLAB. With specific commands, the evaluation was done in each time step and the parameter of the VISSIM object, signal control was changed.

The corroboration of the estimation scheme was done with the simulated density obtained from VISSIM. The vehicle flow at 15 minute intervals were given as the input to VISSIM. Traffic signals were placed at the entry and the exit intersection with fixed green times of 32 s and 60 s respectively for a 100 s cycle time. Three virtual detectors were placed at locations A, B and C as shown in Fig. 2. The required data for estimation scheme was extracted for every time step h of 100 s and the simulated density was calculated using input-output technique [May (1990)]. Online estimation of an over saturated traffic scenario was done using VISSIM COM interface where the data for each time step from VISSIM was processed using MATLAB. Sample result of the estimation scheme is shown in Fig. 5 for which the error was quantified using mean absolute percentage error (MAPE) and was found to be 0.8 %, which indicates accurate estimate.

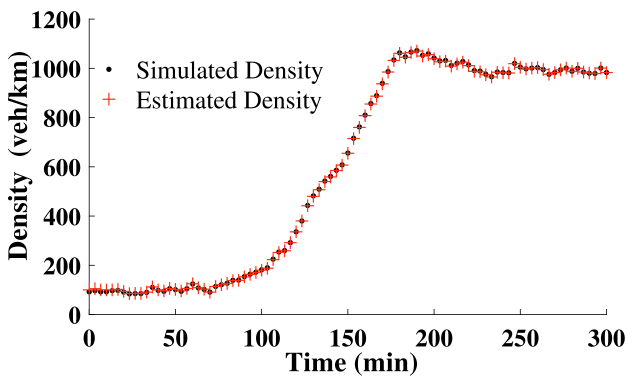

Fig. 5. Corroboration of estimation scheme

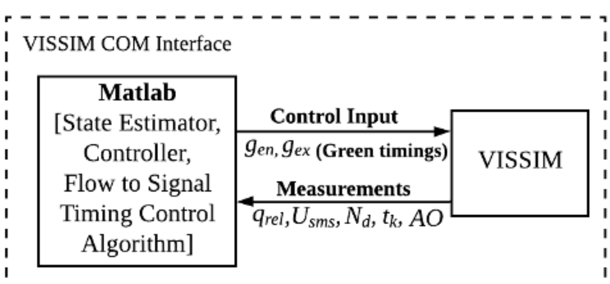

Fig. 6. Simulation environment for closed loop control

The simulation environment for closed loop control is shown in Fig. 6. The estimator implemented in MATLAB estimates the density with the data from VISSIM. The control input and the green times were calculated in MATLAB. The calculated green times were provided to VISSIM and the cycle continues. The effect of control on density was evaluated by considering two scenarios, with and without control scheme and is shown in Fig. 7. In scenario without controller (fixed green time) the density went close to jam density (1300 veh/km), which is not desirable. Hence, the density in the section was maintained at an optimum value corresponding to maximum flow, which is half of jam density (650 veh/km).

In the scenario with control, when the density reached 650 veh/km, the controller was activated. The developed control scheme was able to maintain the density at the desired value. The relative flow from VISSIM and the

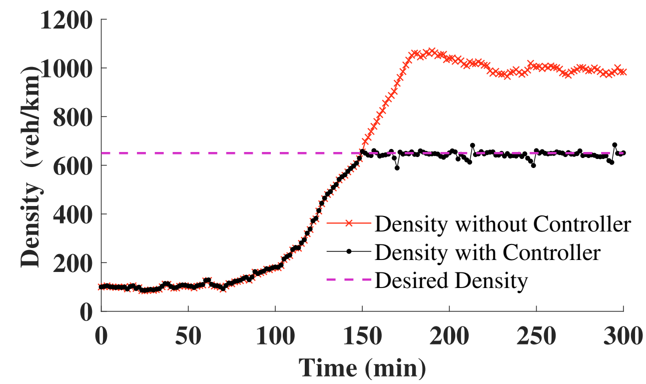

Fig. 7. Density with and without controller

control input is shown in Fig. 8. Based on the control input, a green time was calculated for entry and exit signal control. The resultant flow due to this green time is the relative flow from VISSIM. The difference in these values maybe due to the heterogeneous nature of traffic, which results in random traffic generation in VISSIM.

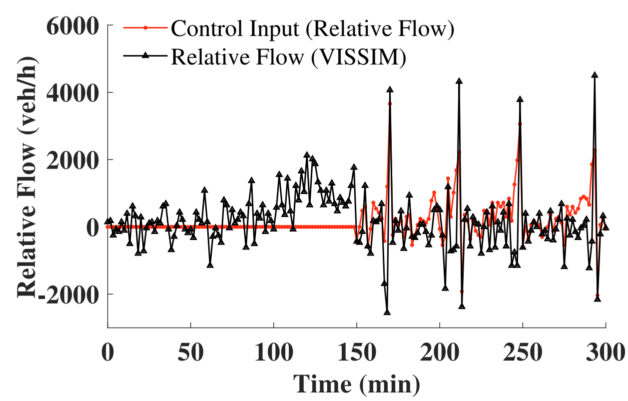

Fig. 8. Control input and relative flow from VISSIM

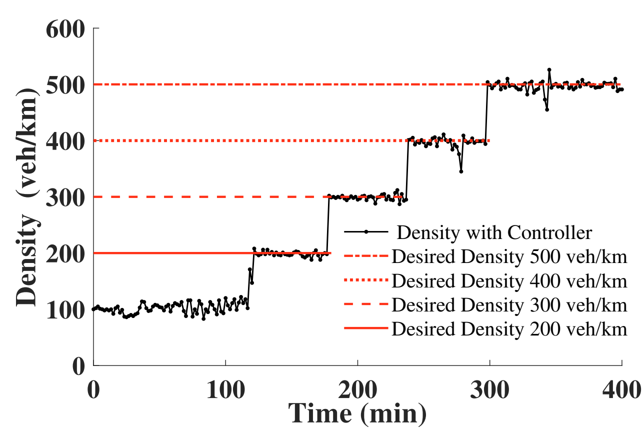

Fig. 9. Density control for different desired values

Further, the tracking performance of the developed control scheme was evaluated by setting different desired values for density. The controller was designed to maintain four different desired values each for 1 h. Figure 9 shows the result which indicate a good tracking capability. The control input and the relative flow from VISSIM are shown in Fig. 10. It can be observed that during the transition from one desired value to another, the control input, relative flow attains a positive peak, allowing more vehicle entry. This illustrated the efficacy of the developed controller in tracking a time varying desired density profile.

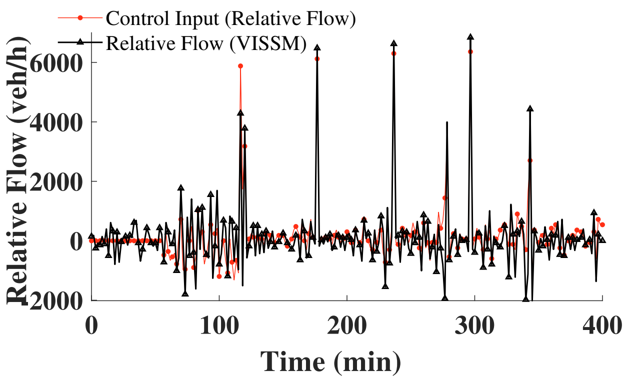

Fig. 10. Relative flow from VISSIM and control input

6. CONCLUSION

A model-based control scheme for controlling traffic at signalised intersections has been developed in this paper. The traffic system was modelled as a non-continuum macroscopic model with state density describing the traffic inside the section. To account for the heterogeneous and lane less nature of the traffic, area occupancy was used as the measurement variable. Density was estimated using an adaptive Kalman filter that considers the measurement noise variation. A state feedback controller was designed to maintain the traffic density in the mid-block section by controlling the traffic signal. VISSIM-MATLAB interface environment was used to implement the developed control scheme along with estimator. The implementation showed promising results indicating the effectiveness of the developed control scheme. Performance in terms of delay or queue can be explored further to evaluate the efficacy of the developed control scheme to extend it to the network level.

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