Performance Evaluation of Alternative Traffic Signal Control Schemes for an Arterial Network by DES Approach-Overview

Jennie Lioris[1] Pravin Varaiya[2] Alexander Kurzhanskiy[3]

[1]ENPC, France, jennie.lioris@enpc.fr
[2]California PATH, University of California, Berkeley USA, varaiya@berkeley.edu
[3]California PATH, University of California, Berkeley USA, akurzhan@berkeley.edu

Abstract

Evaluation aspects of alternative traffic signal control strategies for an arterial network are studied. The traffic evolution of a signalized road network is modelled as a Store and Forward (SF) network of queues. The system state is the vector of all queue lengths at all intersections. The signal control at any time permits certain simultaneous turn movements at each intersection at pre-specified saturation rates. Two control categories, open loop and traffic-responsive policies are compared under fixed and time-varying demand. The behaviour of the underlying queuing network model manifesting asynchronous nature over time while involving concurrence is modelled according to an event-driven approach virtually reproduced by discrete event simulations. Exploration of the implementation outputs results a pertinent mathematical framework for traffic movement, analysis and signal control design. Subsequently, various metric measurements such as queue bounds, delays, trajectory travel times quantify the actual policy. Moreover, aggregate behaviour as in a macroscopic queuing model is also prompted. Experiments are performed using real data for a section of the Huntington-Colorado arterial adjacent to the I-210 freeway in Los Angeles. Lastly, the meso-micro simulation issues resulting from the employed decision tool, PointQ, are compared with microsimulation and mesosimulation forms of other traffic simulation programs.

Keywords: traffic responsive signal, adaptive control, pre-timed control, max-pressure practical policy, discrete event simulation

1 Introduction

The *management* of an arterial traffic network is considered. Currently open loop plans are frequently employed often associated with optimised offsets aiming to create green waves in order to minimise trajectory delays. (Muralidharan et al., 2015) studies the traffic dynamics in a network of signalised intersections. It is shown that when the control can accommodate the demand then the network state converges towards a periodic orbit while any effects of the network initial state disappears. Adaptive controls are expected to improve the network performance since they the current network state is taken into consideration in real time. (Varaiya, 2013) studies a traffic-responsive "Max-Pressure" traffic control, (Mirchandani and Head, 2001) proposes an adaptive control predicting demand patterns and queues to compute timings to minimize average delay. (Aboudolas et al., 2009) suggests an optimal formulation designing a feedback policy. Research studies (Gomes et al., 2008) characterise the behaviour of the cell transmission model of a freeway divided into N cells each with one on-ramp and off-ramp. It is shown that ramp metering eliminates wastefulness of freeway resources.

The present work, appraises the performance of versions of the adaptive Max-Pressure algorithm under unpredicted demand fluctuation. In particular, feedback signal control designs and their related effectiveness are presented and analysed when applied to a network while they are also compared with open loop schemes. Queueing models are employed when designing closed loop signal control plans evaluated by queue based criteria such as queue delays. Thus, traffic evolution is modelled as a controlled store and forward (SF) queuing system. Identified vehicles arrive in iid (independent, identically distributed) streams at entry links, travel along non-saturated (internal) links, join appropriate queues and leave the network upon reaching exit links. At each time and at each intersection, a set of simultaneously compatible movements or *phases* is actuated. Vehicles are discharged at a service rate determined by the *phase* saturation flow rate. When finite internal link capacities are considered, the vertical point queues become horizontal in the sense that interfere in the link vehicle storage capacity and the related link travel times.

A separate queue is considered for each turn movement at each intersection.

Aiming at evaluating the network performance under different control policies a decision making tool is necessary in order to virtually reproduce the considered structure (intersection node and links, vehicle movements and the related control plans) under multiple traffic conditions for both closed and open loop actuation plans. Thus, measurements of various metrics such as delays, travelled times, vehicle queues etc. will be able to quantified according to the employed strategy.

When considering "driver-behaviour", differential equations are required, emulating "car-following" and "lane-changing" aspects. Microsimulation models are necessary for which queue sizes are not state variables and saturation flow rates are not input data. Instead, they are derived from the simulation analysis. Consequently, it is not possible to relate delays to timing schemes and these models are unsuitable for traffic control conception.

Macroscopic simulators often based on the cell transmission model (CTM) (Lo, 2001) represent traffic flow as a fluid. Spatial density is required as a state variable which is hard to measure. Furthermore, modelling turns, shared lanes, queues or introducing sensor behaviour for actuated signal control, under such approach is rather a hard work.

A made-to-measure micro-meso simulation decision making tool called *PointQ* maintaining the identity of each single vehicle while ignores the vehicle interaction is introduced. It has minimal data requirements and receives saturation flow rates as explicit input values. The PointQ decision tool is developed according to discrete event approach (Baccelli et al., 1992) in order to accurately reproduce the evolution of the asynchronous system while it is appropriate for modelling open and closed loop timing control schemes.

The rest of the paper is organised as follows. Section 2 presents the problem formulation and briefly recalls the utilised control schemes. Section 5 introduces PointQ and reasons the employed model approach. Section 5 and Section 6 discuss the performed experiences. Finally, Section 7 compares PointQ with other micro and mesosimulation modes.

2 Traffic Regulation: Stage selection

The simultaneously compatible movements of an intersection are represented by a binary matrix U, the *intersection stage* of which the (i,j) entry equals one if the corresponding phase is actuated, zero otherwise. Let $\mathscr{U}$ be the set of admissible *stages* of a given intersection and $\gamma(l,m)$ the turning ratio of phase (l,m), expressed as the probability of a vehicle to choose as destination link m when joining link l. The optimisation horizon is divided into intervals or cycles of fixed width, each one comprising of T periods. Within each cycle, there exist $T-L$ available planning periods where $L<T$ represents the idle time corresponding to pedestrian movements, amber lights, etc. Let q be the array of which the (i,j) entry is the length of queue related to phase (i,j). The system state at time $t, X(t)$ is defined by $X(t)=q(t)$. A control *stabilises* the network, if the time-average of every mean queue length is bounded. At a given time *stage* $u(t)=U, U\in\mathscr{U}$ and $\lambda_{u(t)}$ cycle proportion have to be decided such that:

- $u(t)$ *stabilises* $X(t)$
- if $\tilde{c}(l,m)$ denotes the service rate of phase (l,m) and f_l represents the vehicle flow in link l, then the following stability condition has to be verified,

$$\tilde{c}(l,m) > f_l\gamma(l,m), \tag{1}$$

- $\sum_{u\in\mathscr{U}} \lambda_u T + L \leq T.$

3 Signal Control Schemes

A brief description of the utilised traffic control algorithms is now presented. The related theory is explicitly developed and analysed in (Varaiya, 2013).

3.1 Pre-timed network control

A *fixed-time* control (FT) is a periodic sequence, $\{\lambda_U,\, U\in\mathscr{U}\}$, actuating each *stage* $u(t)=U^i$, $U^i\in\mathscr{U}$ for a fixed duration $\lambda_{U^i}T$ within every cycle of T periods.

3.2 Max-Pressure Practical (MPract)

Max-Pressure is a distributed policy selecting a stage to actuate as a function of the upstream and downstream queue lengths. The pressure $w(q(t),U)$ exerted by *stage* $U\in\mathscr{U}$, is defined by

$$w(q(t),U) = \sum_{(l,m)} \varsigma(l,m)(t) S\circ U(l,m)(t) \tag{2}$$

where

$$\varsigma(l,m)(t) = \begin{cases} q_{(l,m)}(t) - \sum_{p\in\mathscr{O}(m)} \gamma_{(m,p)} q_{(m,p)}(t), & \text{if } q_{(l,m)}(t) > 0, \\ 0, \text{ otherwise.} \end{cases} \tag{3}$$

At time t, *Max-Pressure* control, selects to actuate the *stage* exerting the higher pressure to the network,

$$U^*(q)(t) = \operatorname{argmax}\{w(q(t),U), U\in\mathscr{U}\}, MP\ stage \tag{4}$$

The MPract algorithm applies the new selected MP stage if significantly larger pressure w,

$$\max_U w(U,q(t)) \geq (1+\eta) w(U^*,q(t)). \tag{5}$$

Parameter η is related to the desired degree of stage switches.

4 Modelling and Simulation Overview

4.1 An event-driven approach

Traffic control constitutes an asynchronous, complex structure where uncertainty and concurrence are naturally inherent. Many theoretical questions related to which models and methods are best to utilise for evaluating the network performance exist. However, one observes that there are queue-based models and car-following models. To our knowledge, all signal control algorithms use queue-based models. Since, we are concerned by signal control designs, a queue-based approach is appropriate to the needs of the study. Queueing theory is intended to be *descriptive*, given a model and control policies, after analysis, verification issues examine whether the desired objectives are attained and (potentially) performance is obtained.

A Discrete Event System (DES) is a dynamical system the behaviour of which is ruled by occurrences of different types of events over time rather than fixed time steps. Although time evolves within two consecutive events, the sole responsible for state transitions is the event realisation. Differential equations (developed for the analysis of time-driven systems) form no longer an adequate setting. Simulation means consist a reliable way to describe the DES dynamics.

For the study of the arterial management a mesoscopic-microscopic discrete event decision tool, "PointQ", is developed. Vehicle identities are preserved but driver-interaction is intentionally ignored. Vehicle routes are observed and travel times are measured. Moreover, PointQ requires similar model parameters as macroscopic approaches (network geometry, demand and signal control). Since elementary calibration is required based on commonly available field data, PointQ can efficiently evaluate the influence of traffic control algorithms to the network. However, PointQ is inadequate for studies related to driver behaviour effects or specific network geometry.

In a DES approach the system evolution is represented as a chronological sequence of events of the form $\{\ldots, s_i, e_i, s_{i+1}, e_{i+1}, \ldots\}$, where s_i is the system state at time t_i and e_i is an event occurring at time t_i marking changes to the system bringing it to state s_{i+1} and so forth. It is assumed that the system is *deterministic* in the sense the state resulting from an event realisation is *unique*. PointQ model involves events on vehicle arrivals, departures and signal actuation.

4.2 PointQ design

The entire structure is split into two independent but also closely interacting parts according to the task nature. The mechanical part virtually represents the system entity interactions. It receives tow types of entries:

- input data such as network geometry (link capacity, speed limit or mean travel time, turn pocket capacity, phase saturation flow rates which can either be measured or estimated during implementations), initial traffic state, sensors etc.
- controls ruling the system.

On the other hand, the real time management comprised of all the decision algorithms required by the mechanical part involving signal controls, vehicle arrival/departure decisions, demand patterns, routing algorithms, queue estimation models etc.

5 Case Study-Data description

A section of the Huntington-Colorado arterial near the I-210 freeway in Los-Angeles, comprised of 16 signalised intersections, 76 links and 179 turn movements, is considered. Figures 2 and 3 illustrate the network map and its abstraction as a directed graph. Stochastic (Poisson) external arrivals are employed, generating approximatively 14,500

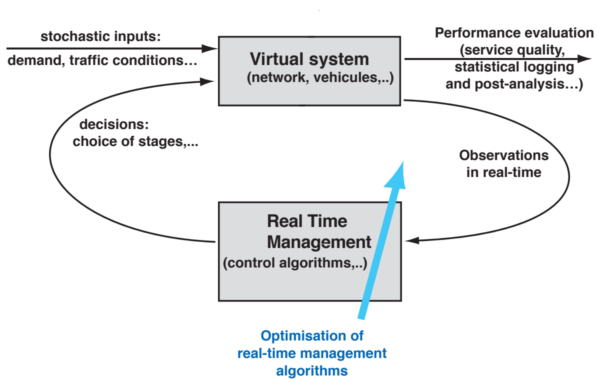

Figure 1. The simulator in two parts.

vehicles per hour. Utilisation of an identical demand contributes to the accuracy of measurements related to the influence of each control scheme on the network. Vehicle routing is based on turning probabilities. The Fixed-Time plan and the turn ratio values are provided by the local traffic agency. The cycle T is of 120 seconds (with some exceptions at two nodes where the cycle is of 90 and 145 secs). The idle duration corresponding to each cycle is between 0 and 2 seconds. Internal links are of finite vehicle storage capacity. Stochastic travel times based on the free flow speed and the current link state are considered. Time granularity is taken equal to 0.1 seconds while the network evolution is reproduced over a period of 3 hours.

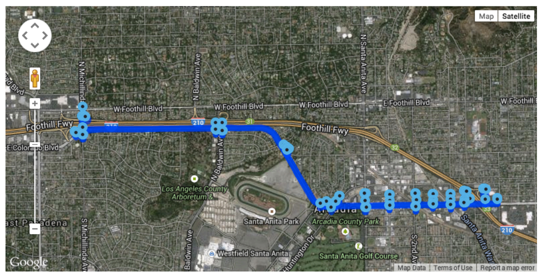

Figure 2. Huntington-Colorado site map.

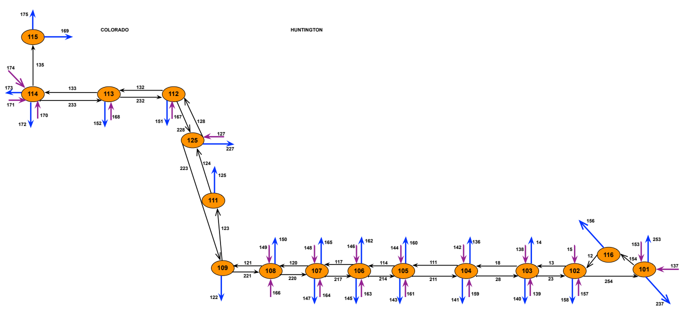

Figure 3. Directed Network graph.

6 From theory to applications

In what follows, we focus on the network performance evaluation for both timing plans, FT Offset and MPract. Metrics on queue lengths, travel times and delays are investigated for two demand patterns, the baseline demand provided by the data and a time-varying one.

6.1 System Stability

Figure 4 plots the network state evolution for both the Pre-timed and MPract signal controls. The theoretically expected demand accommodation is also experimentally verified. Moreover, one observes that the feedback plan (blue curve) maintains lower queue values.

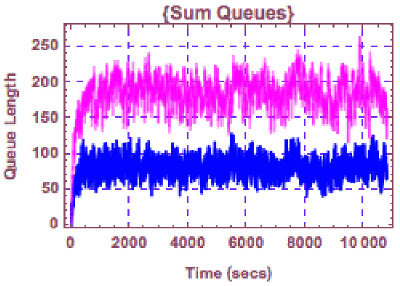

Figure 4. Sum network queues: MPract 8-blue curve, FT Offs-purple curve.

6.2 Trajectory Delay Measurement

For each realised trajectory (sequence of entry, internal and exit links) delays faced by all vehicles followed the related path are measured. The corresponding distribution is computed and the CDF function is represented in Figure 5. MPract (purple curve) reduces delays almost four times in comparison with the fixed time plan (green plot).

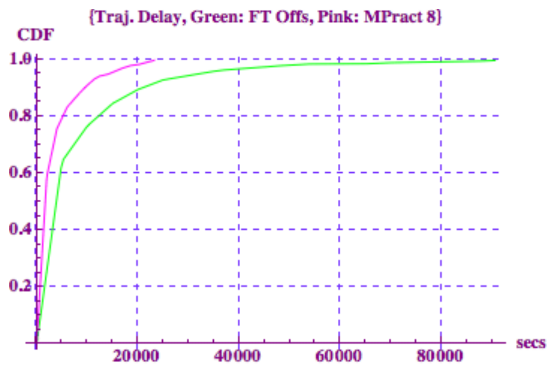

Figure 5. CDF Trajectory Delays: MPract (purple), FT-Offs (green).

6.3 Queue Delay Measurement

Delays on distinct queues on link 114 (incoming link at node 106, Huntington region) are now measured.

Three phases are associated with link 114. Figures 8, 9 and 10 depict the evolution of cumulative delay values for each phase according to the Pre-timed and MPract policies. Observe that for phase $(114,145)$ the pre-timed scheme implies lower delays. Mainly, this is due to the fact that $q(114,145)$ and $q(114,145)$ head vehicles towards exit links. More precisely, phases $(114,145)$ and $(217,214)$ are simultaneously actuated by stage 1. Similarly phases $(114,117)$ and $(217,214)$ are actuated by a concurrent stage 2. At any decision time the MPract stage is the one exerting the higher pressure. According to equation 2 and since no output queues are associated with the exit links 145, 162, the pressure exerted by stage 2 is determined by the queue lengths of the related phases. Taking into consideration the flows and queue demand on link 114, stage 2 often exerts higher pressure regarding stage 1. Thus, it receives increased green time duration. Figures 6, 7 plot the evolution of queues $q(114,145)$ and $q(114,117)$ for both policies. Lower queues result under MPract for phases of stage 2. The evolution of cumulative delay values for each phase of link 114 is represented in Figures 8, 9 and 10 (saturation flow rates remain unchanged for both policies).

Tables 1, 2 resume the mean time spent by vehicles in four queues and the average vehicle sojourn time in all queues respectively. Obviously, MPract appears more refined although for phase$(170,173)$ FT-Offset implies smaller delays. Table 3 presents the total travel time between three entry-exit links.

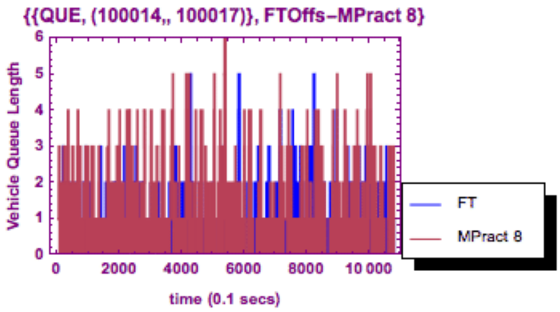

Figure 6. Evolution q(114,117), FT Offs-MPract 8.

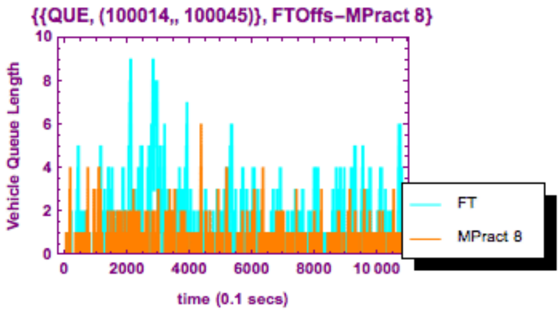

Figure 7. Evolution q(114,145), FT Offs-MPract 8.

6.4 Varying Traffic Conditions

The network stability is now examined under time-varying traffic intensity. During a given period, demand gradu-

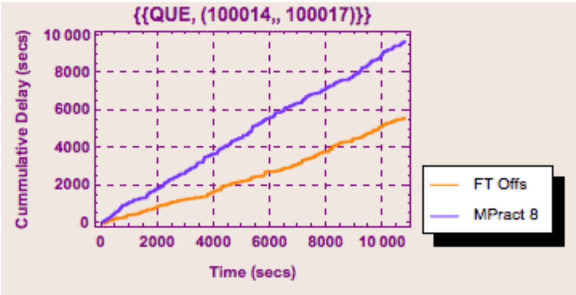

Figure 8. Cumulative Delay q(114,117), FT Offs-MPract 8.

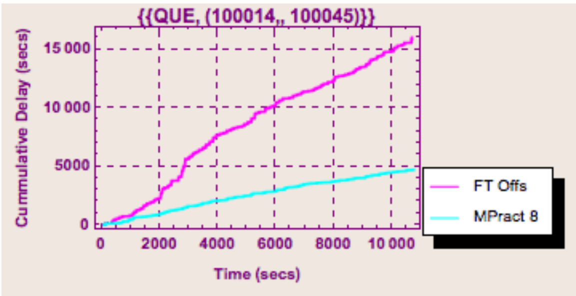

Figure 9. Cumulative Delay q(114,145), FT Offs-MPract 8.

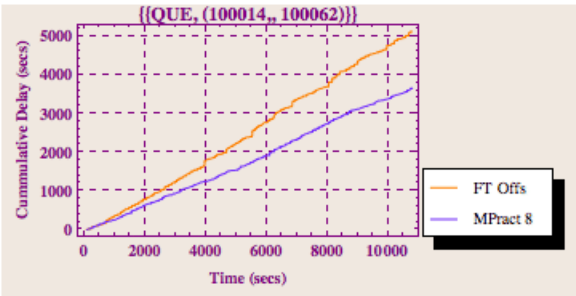

Figure 10. Cumulative Delay q(114,162), FT Offs-MPract 8.

Table 1. Mean Time spent by vehicles in queue.

Que ID		Mean Veh. Sojourn Time (secs)	Mean Veh. Sojourn Time (secs)
		MPract	**FT Offs**
164	1020	49.96	79.72
167	228	12.16	51.32
117	120	10.72	33.35
170	173	78.46	49.61

Table 2. Average Mean Time spent by vehicles in all queues.

AVERAGE MEAN VEH SOJOURN TIME IN QUEUES	MPract (secs)	FT Offs (secs)
	12.05	22.32

Table 3. Travel Time Entry-Exit Link.

Entry link	Exit link	Travel ttime (secs)	Travel time (secs)
		MP	**FT Offs**
127	145	204.4	230.8
164	173	364.7	462.2
138	1069	395.2	519.6

ally increases and potentially temporary congested conditions may result (representing peak hours or unpredicted demand variation). Thus, within period $[0, 36, 000]$ external demand increases every two hours by a factor c_1 equal to $1.05, 1.15, 1.3, 1.5$. For the following two hours, that is from $t = 36000.1$ to $t = 43, 200$ seconds, demand decreases every half an hour by a factor c_2 taking progressively values $1.3, 1.15, 1.05, 1$.

Figure 11 illustrates the evolution of all the network queues when the pre-timed actuation durations are employed. While demand remains inferior to $1.15d$ (d is the initial demand level), that is while time $t < 14, 000$ secs the system remains stable. Congestion spreads during period $[14, 400, 36, 800]$ when the current demand intensity values $1.15d$, $1.3d$, $1.5d$. During this time a significant portion of the network links become congested, strongly increasing the number of vehicles in the network. Obviously, this Fixed-Time plan cannot accommodate the new demand intensity. The resulting FT behaviour is theoretically expected from the stability condition presented in §2. When the demand level decreases link saturation progressively diminishes (from $t = 36, 000$ to $43, 200$ seconds).

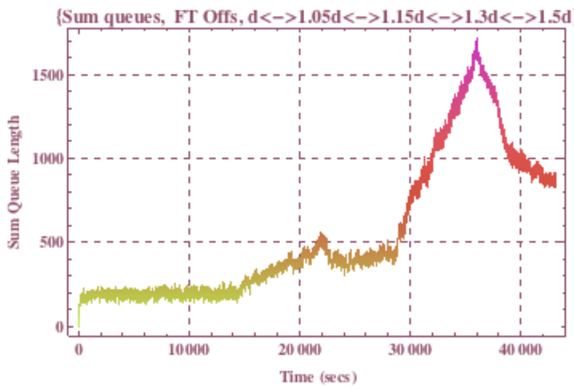

Figure 11. Evolution sum queues, varying demand level, FT Offset.

In contrast, the network behaviour differs when a MPract policy defines signal plans. Figure 12 depicts the sum of the network queues for the $c_i d$, $i = 1, 2$ demand intensities. Clearly, the feedback policy prohibits link saturation. The sum of all the network queues rises during period $[21, 600, 36, 000]$ when a 30% and 50% increase of the initial demand takes place but still the network remains stable.

Figures 13 and 14 plot the aggregate entry (blue

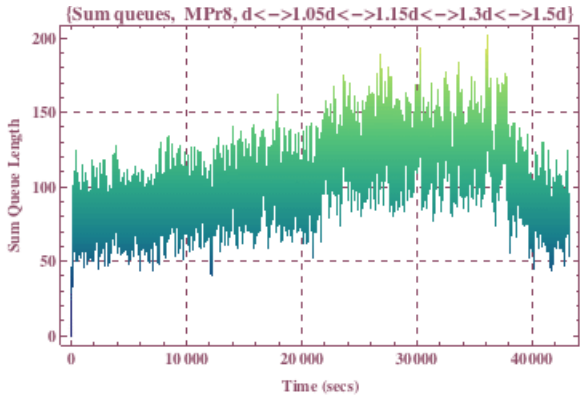

Figure 12. Evolution sum queues, varying demand intensity, MPract 8.

curve) end exit flows (red, purple curves) during period [29,000, 31,000] for FT and MPract policies respectively. Since, the pre-timed control cannot accommodate $c_1 d$, demand for $c_1 = 1.3, 1.5$ the number of vehicles exiting the network drops below the external arrivals. This phenomenon disappears under MPract.

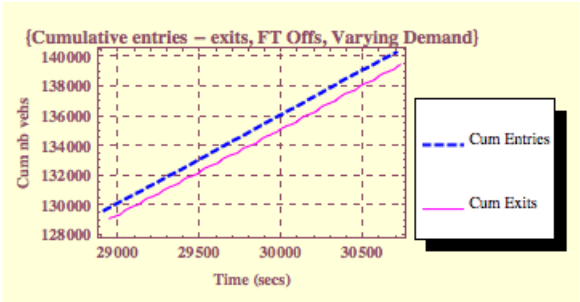

Figure 13. Aggregate entries-exits, varying demand, FT Offs.

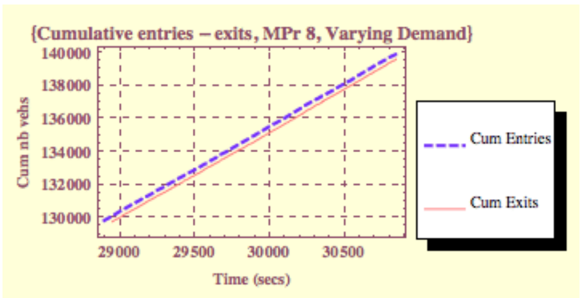

Figure 14. Aggregate entries-exits, varying demand, MPract 8.

7 PointQ versus AIMSUN Network Performance

As previously discussed, PointQ is a micro-meso decision tool, approaching a SF network queue model by a discrete event technique.

AIMSUN is a vehicle traffic software offering mesoscopic, microscopic and hybrid simulation approaches.

Aiming at a comparison of the two simulation tools, the section of Huntington-Colorado arterial is modelled in AIMSUN. Both approaches employ stochastic demand of intensity d (baseline demand), Pre-timed signal plan as governing control and consider the turn ratio values and link free flow speeds as provided by the data. Microscopic and Mesoscopic AIMSUN simulations are performed for a three hours duration. The state of intersection 101 (first node at the Huntington area) is investigated according to PointQ and AIMSUN implementations.

Five controlled movements exist at node 101 corresponding to queues $q(137, 154)$, $q(153, 154)$, $q(153, 237)$, $q(254, 237)$ and $q(254, 253)$. We focus on the behavior of two representative movements. Phase $(137, 154)$ brings vehicles into the network from the entry link 137 and head them towards the internal link 154 while phase $(254, 237)$ moves vehicles from the internal link 254 towards the exit link 237.

7.1 Evolution of phase $(137, 154)$

Figure 15 represents the evolution of queue $q(137, 154)$ under a PointQ simulation. Figures 16 and 17 illustrate the queue behaviour when micro and meso AIMSUN simulations are performed.

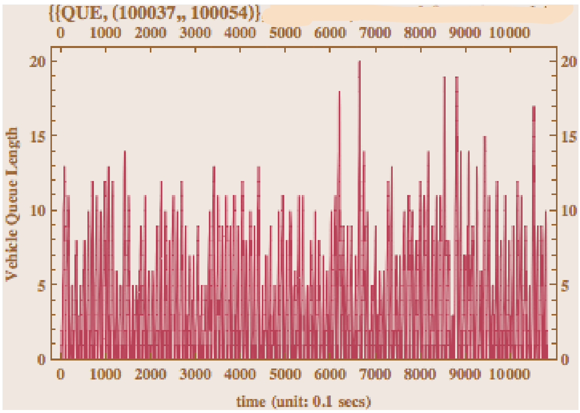

Figure 15. Evolution of q(137,154), PointQ.

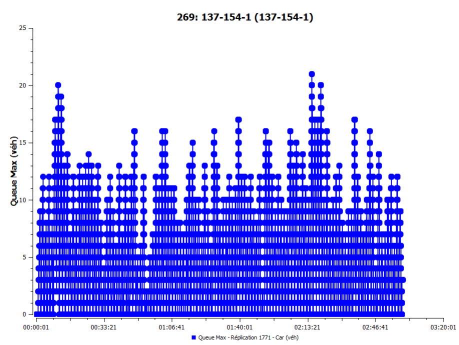

Figure 16. Evolution of q(137,154), AIMSUN Micro.

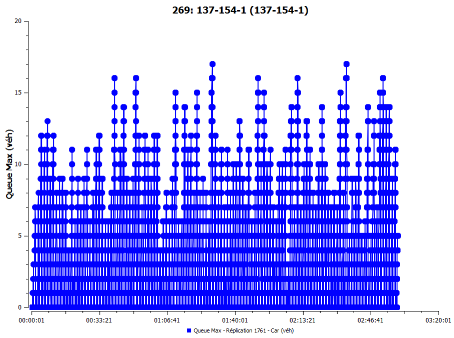

Figure 17. Evolution of q(137,154), AIMSUN Meso.

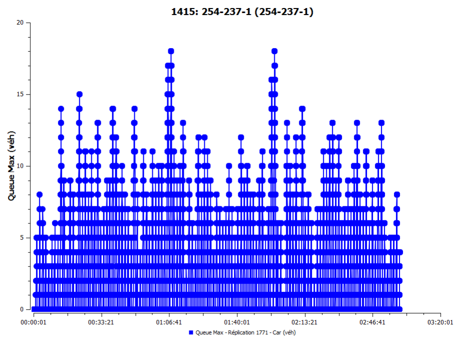

Figure 19. Evolution of q(254,237), AIMSUN Micro.

Although stochastic external demand and link travel times are considered, one observes that the three approaches, PointQ model and AIMSUN micro and meso versions provide close results. Queues resulting from the three simulation modes verify the theoretically resulting stability. Furthermore, queue lengths vary within similar bound values over time.

7.2 Evolution of phase $(254,237)$

Figure 18 plots the behaviour of queue $q(254,237)$ when PointQ while Figures 19 and 20 describe the resulting queue state under micro and meso AIMSUN approaches.

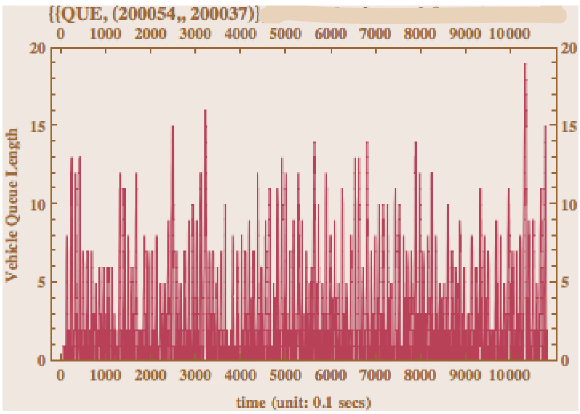

Figure 18. Evolution of q(254,237), PointQ.

As in the case of phase $(137,154)$, queue $q(254,237)$ shows the same behaviour for both PointQ and AIMSUN models and all modes (micro-meso, micro and meso).

An extended analysis of all the network queues implies that the resulting network state is similar under the two models.

8 Conclusions

Aiming at a further improvement of traffic, new signal schemes are designed, evaluated and potentially optimised before a real time application. The key contribution of this paper is to present the extended options of a microscopic-mesoscopic decision tool, called PointQ destined for an

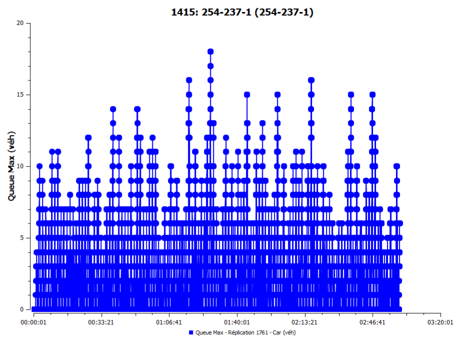

Figure 20. Evolution of q(254,237), AIMSUN Meso.

an ameliorated study of arterial traffic. PointQ relies on the principle of discrete events and models arterials as a Store and Forward queuing network. Thus, queues form state variables of the system. Minimal explicit input information is needed amongst which the saturation flow rates. These values are necessary to signal control development since most feedback algorithms follow queue-based approaches. Experiments are performed under real data for a section of Huntington-Colorado near Los Angeles. Two control policies are employed, Pre-timed and Max-Pressure Practical plans under fixed and time-varying demand intensity. The expected theoretical results concerning the network stability are verified and the network performance is quantified in terms of queue bounds, delay metrics and travel times. Finally, PointQ accuracy is observed in comparison with a simulation program providing both micro and meso simulation modes. Useful directions of future work worthing to be pursuing is the development of queue estimation algorithms, employed in feedback controllers (e.g. versions of MP algorithm) and actuated controls as well. Moreover, introducing additional modes of sensor behaviour the combination of which would improve precision in the computational results (actuated controls).

References

K. Aboudolas, M. Papageorgiou, and E. Kosmatopoulos. Store-and-forward based methods for the signal control problem in large-scale congested urban road networks. *Transportation Research Part C-Emerging Technologies*, 17:163–174, 2009.

R. E Allsop. Delay-minimizing settings for fixed-time traffic signals at a single road junction. *IMA Journal of Applied Mathematics*, 8(2):164–185, 1971.

F. Baccelli, G. Cohen, J.Olsder, and J.P.Quadrat. *Synchronization and Linearity – An Algebra for Discrete Event Systems*. Wiley, 1992. ISBN ISBN 0 471 93609 X.

G. Gomes, R. Horowitz, A. Kurzhanskiy, J. Kwon, and P.Varaiya. Behaviour of the cell transmission model and effectiveness of ramp metering. *Transportation Research Part C: Methodological, 16(4):485-513, August 2008*, 2008.

B.G Heydecker. Objectives, stimulus and feedback in signal control of road traffics. *Journal of Intelligent Transportation Systems*, 8:63–76, 2004.

H. K Lo. A cell-based trafic control formulation: Strategies and benefits of dynamic timing plans. *Transportation Science*, 35(2), 2001.

P. Mirchandani and L. Head. A real-time traffic signal control system: Architecture, algorithms, and analysis. *Transportation Research Part C-Emerging Technologies*, 9(6):415–432, 2001.

A. Muralidharan, R. Pedarsani, and P.Varaiya. Analysis of fixed-time control. *Transportation Research Part B: Methodological, 73:81-90, March 2015*, 2015.

TRB. Highway Capacity Manual. Technical report, Transportation Research Board, 2010.

P. Varaiya. Max pressure control of a network of signalized intersections. *ACM Transactions on Mathematical Software*, 2013.