Proceedings of the 2015 ORSSA Annual Conference
pp. 44–53
www.orssa.org.za/wiki/uploads/Conf/2015ORSSAConferenceProceedings.pdf

ORSSA Proceedings
ISBN
978-1-86822-666-5

An evaluation of self-organisation in traffic control with respect to varying distances between adjacent intersections in a road corridor

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Abstract

Traffic congestion is a major concern in most cities all over the world. The economy, health of the population and the environment are all affected negatively by heavily congested roads. A recently proposed solution to ease traffic congestion in busy road networks involves the implementation of self-organising signal control algorithms at signalised intersections. In particular, an algorithm inspired by the theory of inventory control, an algorithm inspired by the chemical process of osmosis and finally an algorithm that is a hybrid of the first two have recently been proposed for traffic control at signalised intersections. These algorithms seem to be promising in terms of reducing vehicle delays as well as the propagation of uninterrupted traffic flow, known as *green waves*, through adjacent intersections. These three self-organising algorithms have previously been compared to an existing fixed-time algorithm as well as to two other existing self-organising algorithms. This comparison took place in a simulated environment facilitating the calculation of a number of performance measure indicators in order to determine which algorithms were most effective. The results revealed that in a corridor road network, the hybrid algorithm outperformed the others overall, while in a grid road network, the osmosis-inspired algorithm was the most effective. These results were, however, obtained under the assumption that neighbouring intersections were equally spaced from one another, which is a highly unlikely occurrence in practice. In this paper, the algorithms are compared in a more realistic, simulated environment where neighbouring intersections lie at varying distances from one another. It is verified to what extent the self-organising algorithms still outperform the existing algorithms by facilitating the formation of so-called green waves of uninterrupted traffic flow through adjacent intersections in the context of this added complexity.

Key words: Traffic signal control, Self-organisation.

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1 Introduction

The main cause of traffic congestion is the over-utilisation of roads which leads to dense, stop-and-go traffic [6]. A viable method of reducing traffic congestion involves optimisation of traffic signal control algorithms employed at signalised intersections. Improved traffic signal control may serve to dilute concentrated traffic in road networks by increasing the efficiency of signal duration times, leading to reduced vehicle delay and a more dispersed use of road networks. There are two main types of traffic signal control: *fixed-time control* and *vehicle-actuated control*. Fixed-time control consists of the specification of predetermined signal cycle times based on expected traffic flow densities for various times of the day. Since traffic volumes often fluctuate dramatically over the course of a single day, actual demand is typically not met by such predetermined cycle times and, as a result, green times are often either too long or too short. Vehicle-actuated control, on the other hand, is capable, at least to some extent, of adapting according to real-time traffic conditions, by selecting cycle phases and signal timings to best suit the current conditions of the road network. Unlike fixed-time control, vehicle-actuated control is responsive to changes in traffic flow, but requires the implementation of vehicle detection equipment in order to register the prevailing traffic conditions.

The optimisation problem associated with centralised traffic signal control is NP-hard and realistic instances of this problem typically cannot be solved in real time [7, 10]. The use of a decentralised traffic control system is advantageous as the problem of traffic control at each intersection may be viewed as an isolated problem, requiring no information on how signals are controlled at neighbouring intersections. The decentralised paradigm of *self-organisation* has been suggested as an appropriate approach toward developing effective traffic signal control algorithms. Self-organisation occurs when there is an increase in the order present in a system without any form of external control [3]. It may be an effective approach to traffic control, not only because it is decentralised, but also because it can lead to the natural *emergence* of coordination between intersections. Such emergence is observed when the system exhibits novel behaviour on a macro level as a result of interactions between system elements at the micro level [3]. Three self-organising traffic signal control algorithms recently proposed by Einhorn *et al.* [4] appear to be effective in terms of being capable of reducing vehicle delay time in road networks. None of these algorithms requires predetermined parameter values, but they require the use of radar detection equipment mounted at each intersection.

The first algorithm is inspired by the theory of inventory control and attempts to minimise the virtual costs associated with vehicle delay. The second algorithm is inspired by the chemical process of osmosis, which takes into account the push force of vehicles approaching an intersection as well as the pull force of the empty space on the other side of the intersection which may be occupied by vehicles. The third algorithm is a hybrid of the first two, attempting to exploit the best characteristics of both, while simultaneously maximising the intersection utilisation.

These three algorithms were compared by Einhorn *et al.* [4] in a specially designed simulated road network. The simulation model was, however, only able to accommodate road networks with equally spaced intersections, which is not a realistic assumption. The objective in this paper is to evaluate to what extent the algorithms are effective in reducing vehicle delay time when intersections are at varying distances from one another. The reason for this evaluation is the anticipation that in order to generate so-called green waves of uninterrupted traffic flow through adjacent intersections along a road corridor, it is expected to be advantageous if the distances between successive intersections are uniform. The simulation test bed developed by Einhorn *et al.* [4] is generalised in this paper so as to allow for non-uniform spacings between successive intersections along a road corridor. The validity of the findings of Einhorn *et al.* [4] is then tested in this generalised simulation setting.

The paper is organised as follows. A brief literature review is conducted in §2 on the use of self-organisation in traffic signal timings, affording special attention to the three self-organising algorithms proposed in [4]. The design of our simulation experiment is presented in §3, after which the simulation results are reported and interpreted in §4. Some concluding remarks follow in §5 after which the the paper closes in §6 with a number of ideas with respect to possible future work related to the work reported here.

2 Literature review

A brief literature review is conducted in this section on the previous use of self-organisation in traffic control and its associated advantages and shortcomings.

2.1 Early use of self-organisation in traffic signal timings

The implementation of self-organisation in traffic signal control is a relatively new idea which has yet to be implemented in practice on a large scale. The self-organising approach towards traffic signal control brings with it multiple benefits, including short-term flexibility, long-term adaptability and reduced cost associated with computing time [5, 9]. Gershenson [5] states that traffic signal control is more of an adaption problem, rather than an optimisation problem, due to typically unpredictable changes in traffic volume. He proposed a self-organising traffic signal control algorithm called *SOTL-request*. This algorithm gives right-of-way preference to platoons of vehicles rather than to individual vehicles, in order to promote the uninterrupted migration of large groupings of vehicles through an intersection during a single signal phase. This is achieved by changing a red signal once the number of vehicles queued at an intersection reaches a certain threshold, while if this number falls below the threshold, the signal remains red for longer, allowing time for more vehicles to join the queue [2, 5]. A variation on this algorithm, called *SOTL-phase*, incorporates an additional minimum time constraint in order to prevent rapid switching of signals. A third algorithm, known as *SOTL-platoon* is similar to *SOTL-phase*, but with additional restrictions designed to regulate the size of the platoons that travel through the intersection. The latter algorithm was compared to the widely implemented SCATS algorithm [8] in a simulated environment and was shown to significantly outperform it [12]. The three self-organising algorithms mentioned above have been described as robust, but a common disadvantage of these algorithms is that a number of parameter values must be determined in order for them to work effectively. It is, however, not stated in the literature how to go about selecting appropriate parameter values for a given traffic scenario [4].

Another example of self-organisation in traffic signal control has been proposed by Lämmer and Helbing [7]. Their algorithm was inspired by the oscillatory changes in the counter-flow of pedestrians through a narrow bottleneck. The algorithm makes use of a strategy combining optimisation and stabilisation in the road network. The optimisation phase aims to minimise total vehicle delay experienced by vehicles that are within a certain distance from the intersection. In order to prevent queues from growing too long, the stabilisation phase attempts to keep the maximum vehicle queue length below a certain threshold. This algorithm was shown in [4] to be effective in reducing vehicle delay and outperformed existing state-of-the-art adaptive control schemes. It is also capable of outperforming any solution based on fixed-time control cycles provided that the parameter values of the algorithm are chosen judiciously [10].

2.2 The self-organising algorithms of Einhorn et al.

As mentioned in the introduction, three traffic signal control algorithms were proposed in [4], each inspired by a self-organising process.

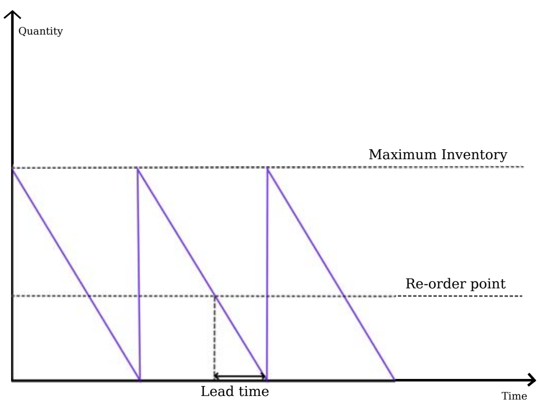

Figure 1: *Demand in the basic EOQ model.*

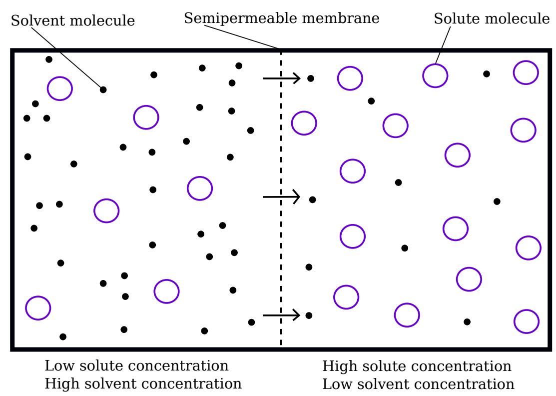

Figure 2: *The process of osmosis.*

2.2.1 An algorithm inspired by inventory control

The first of the algorithms by Einhorn *et al.* [4] is a self-organising algorithm known as the *inventory traffic signal control algorithm* (I-TSCA), which is based on the theory of inventory control and attempts to minimise a virtual cost associated with the total delay time of vehicles in a network. The *economic order quantity* (EOQ) model in inventory control requires the determination of the reorder point in time as well as the associated reorder quantity of a particular product held in inventory, as illustrated in Figure 1 [11]. In traffic control, these two variables correspond to the point in time at which signal switching must take place and the amount of green time allocated, respectively [4]. The algorithm functions by calculating the total cost associated with allocating green time to each signal phase, selecting the phase which results in the lowest total cost and awarding it green time. The use of radar detection technology at intersections is assumed as a prerequisite for implementing the algorithm so that the number of approaching vehicles can be observed, as well as their associated speeds and distances from the intersection, in order to facilitate the calculation of the "demand" for each signal phase. In [4] it was found that the I-TSCA performed most effectively in uniformly spaced road corridors and city grid topologies under lighter traffic conditions, due to the fast switching propensity of the algorithm.

2.2.2 An algorithm inspired by osmosis

If two liquids of different solute concentrations are separated by a semipermeable membrane such that the solute molecules cannot pass through it, the solvent molecules of the liquid with a lower solute concentration pass through the membrane into the liquid with the higher solute concentration [1]. This is known as the *process of osmosis*, depicted in Figure 2, and results in a balance of the solute concentration on both sides of the membrane through pressure exertion. The presence of these pressures is the reason this process is ideal for implementation in traffic control.

The second self-organising algorithm by Einhorn *et al.* [4] is called the *osmosis traffic signal control algorithm* (O-TSCA). The algorithm likens the solvent molecules in the process of osmosis to vehicles approaching the intersection, which is analogous to the semipermeable membrane through which the solvent molecules (vehicles) pass. The solute molecules correspond to the empty space along the roadway on the other side of the intersection not occupied by vehicles. Vehicles approaching the intersection will exert a push pressure on the system in a manner similar to how solvent molecules are "pushed" through the semipermeable membrane in osmosis, while the empty space just beyond the intersection exerts a pull force on vehicles through the intersection to the empty road space on the other side of the intersection. Einhorn *et al.* [4] found that the O-TSCA performs well in uniformly spaced road corridors and city grid topologies under heavier traffic conditions as it tends to give preference to large platoons of vehicles, switching signals less often.

2.2.3 A hybrid algorithm

Under light traffic conditions it was found that the I-TSCA outperformed the O-TSCA as the latter algorithm tended to award green times that were too long under light traffic conditions, while the faster switching signals of the I-TSCA better suited these traffic conditions. Under heavy traffic conditions, on the other hand, the O-TSCA outperformed the I-TSCA, as mentioned. This is due to the long green times typically awarded by the O-TSCA under such conditions which are indeed necessary to alleviate heavy traffic density, while the I-TSCA switched signals too frequently. A third self-organising algorithm, known as HYBRID, was therefore proposed by Einhorn *et al.* [4], which incorporates both the I-TSCA and the O-TSCA in order to capitalise on the advantages of both algorithms. It employs these algorithms together with an *intersection utilisation maximisation supervisory mechanism* (IUMSM) in order to ensure that the intersection is not under-utilised as a result of green times that are too long or too short.

3 Simulation experiment

We generalised the simulation framework proposed in [4] to account for road networks that do not exhibit equally spaced intersections. Three different scenarios are considered in our simulation evaluation experiment within the paradigm of this generalisation. A corridor roadway comprising four equally spaced intersections is considered in the first scenario (as illustrated in Figure 3), while a corridor of four intersections is also considered in our second scenario, but with the difference that the distance between the middle two adjacent intersections is a multiple of those between the flanking pairs of intersections (as illustrated in Figure 4). Lastly, a corridor of four intersections is yet again considered in our third scenario in which intersections occur at uneven distances from one another (as illustrated in Figure 5).

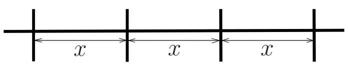

Figure 3: *Scenario 1.*

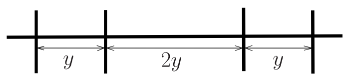

Figure 4: *Scenario 2.*

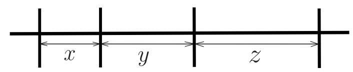

Figure 5: *Scenario 3.*

In each of these three experiments, ten simulation replications are performed under the exact same arrival conditions in order to ensure a fair comparison. In contrast, Einhorn *et al.* [4] performed 30 simulation replications in their experiments, but we found that the difference between the averages of the five *performance measure indicators* (PMIs) over ten replications and over 30 replications was not significant. We adopt the same five PMIs used by Einhorn *et al.* [4], namely, the average mean and maximum vehicle delay time, the average normalised vehicle delay time, the average mean number of vehicle stops made and the average mean normalised number of vehicle stops made.

4 Simulation results

In this section, the performance results of each of the three self-organising algorithms proposed by Einhorn *et al.* [4] are presented for various traffic flow densities for the three scenarios described in §3.

4.1 Scenario 1

The scenario in Figure 3 was already implemented and evaluated by Einhorn *et al.* [4], but the implementation was repeated in this paper for validation purposes. The five PMI values achieved by the three algorithms of Einhorn *et al.* [4] over the ten simulation runs for Scenario 1 are shown in Tables 1 and 2 for light and heavy traffic flow conditions, respectively.

Under light traffic conditions the hybrid algorithm was found to be the best performing algorithm, with a normalised delay time of 1.18 — significantly outperforming I-TSCA and O-TSCA. Although O-TSCA causes longer delay times than Hybrid, O-TSCA is the best performing algorithm with respect to the mean number of stops made in the system. The mean maximum delay experienced by vehicles under O-TSCA was 106.35 — a significantly larger value than those achieved by both Hybrid and I-TSCA.

Algorithm	I-TSCA	O-TSCA	Hybrid
Mean delay time	13.94	17.70	11.80
Normalised delay time	1.22	1.29	1.18
Mean number of stops	1.23	0.81	1.00
Normalised number of stops	0.81	0.55	0.62
Average maximum delay time	95.31	106.35	89.52

Table 1: *PMI results for each algorithm under light traffic conditions in Scenario 1.*

In roadways experiencing a heavier flow of traffic, Hybrid was again the most effective in terms of achieving the lowest average mean delay time of 21.87 seconds, while O-TSCA and I-TSCA obtained corresponding values of 23.67 and 24.63, respectively. Once again, O-TSCA was the most effective with respect to the mean number of stops made, significantly outperforming both I-TSCA and hybrid. O-TSCA also obtained the lowest average maximum delay time of 108.83. Since it was the worst performing algorithm in terms of maximum delay time under lighter traffic conditions, the simulation results suggest that O-TSCA is more efficient for Scenario 1 under heavier traffic.

Algorithm	I-TSCA	O-TSCA	Hybrid
Mean delay time	24.63	23.67	21.87
Normalised delay time	1.39	1.41	1.34
Mean number of stops	1.36	0.92	1.07
Normalised number of stops	0.89	0.65	0.67
Average maximum delay time	131.73	108.83	122.69

Table 2: *PMI results for each algorithm under heavier traffic conditions in Scenario 1.*

4.2 Scenario 2

The five PMI values achieved by the three algorithms of Einhorn *et al.* [4] over the ten simulation runs for Scenario 2 are shown in Tables 3 and 4 for light and heavy traffic flow conditions, respectively.

Under light traffic conditions, the performances of Hybrid and I-TSCA are similar in Scenario 2 to those in Scenario 1, but the performance of O-TSCA is significantly worse. Its average delay time is longer than in the previous scenario although the difference is not statistically significant at a 95% confidence interval. The average maximum delay time of O-TSCA, however, is 199.15, which is significantly worse than the corresponding value of 106.35 achieved by the algorithm in the first scenario.

In heavier traffic conditions, once again, there is very little difference between the performance of hybrid and I-TSCA in this scenario, and with Scenario 1. The performance of O-TSCA worsens (as it did under lighter traffic conditions) as the distances between intersections become non-uniform. The average maximum delay time, for example, increased from 108.83 in the equidistant network of Scenario 1 to 151.60 in the road corridor of Scenario 2.

Algorithm	I-TSCA	O-TSCA	Hybrid
Mean delay time	13.84	23.27	11.90
Normalised delay time	1.22	1.33	1.18
Mean number of stops	1.22	0.86	1.00
Normalised number of stops	0.79	0.51	0.62
Average maximum delay time	90.97	199.15	91.34

Table 3: *PMI results for each algorithm under light traffic conditions in Scenario 2.*

Algorithm	I-TSCA	O-TSCA	Hybrid
Mean delay time	23.66	29.14	21.81
Normalised delay time	1.38	1.45	1.34
Mean number of stops	1.31	1.07	1.07
Normalised number of stops	0.86	0.68	0.67
Average maximum delay time	129.23	151.60	123.90

Table 4: *PMI results for each algorithm under heavier traffic conditions in Scenario 2.*

4.3 Scenario 3

The five PMI values achieved by the three algorithms of Einhorn *et al.* [4] over the ten simulation runs for Scenario 3 are shown in Tables 5 and 6 for light and heavy traffic flow conditions, respectively.

Under low traffic flow densities, the O-TSCA is the only algorithm performing significantly worse in this scenario than it did in Scenario 1. While the mean vehicle delay time is not dramatically different from that in the second scenario, it is 25.94, while originally it was 17.70 in Scenario 1. The average maximum delay time significantly worsened from 106.35 in Scenario 1 (as well as from 199.15 in Scenario 2) to 230.88 in Scenario 3.

Algorithm	I-TSCA	O-TSCA	Hybrid
Mean delay time	13.86	25.94	11.80
Normalised delay time	1.22	1.34	1.18
Mean number of stops	1.23	0.84	1.00
Normalised number of stops	0.80	0.48	0.62
Average maximum delay time	94.28	230.88	89.52

Table 5: *PMI results for each algorithm under light traffic conditions in Scenario 3.*

Under heavier traffic conditions, Hybrid and I-TSCA once again did not yield results that are significantly different from those in Scenario 1. O-TSCA's PMIs are all similar to those of O-TSCA in Scenario 2, obtaining a delay time of 27.41 and average maximum delay time of 148.51. It is also noted that its average maximum delay time is significantly less than the corresponding value under lighter conditions.

Algorithm	I-TSCA	O-TSCA	Hybrid
Mean delay time	24.07	27.41	21.99
Normalised delay time	1.38	0.80	1.34
Mean number of stops	1.34	1.02	1.08
Normalised number of stops	0.87	0.67	0.68
Average maximum delay time	132.02	148.51	130.31

Table 6: *PMI results for each algorithm under heavier traffic conditions in Scenario 3.*

5 Conclusion

From the results in §4 we deduce that varying distances between intersections only seems to have a significant impact on the performance of O-TSCA. This indicates that the effectiveness of this algorithm relies on the equal spacing of intersections in order to perform effectively. Under light traffic conditions we observed that both the mean delay time and the average maximum delay time worsen with a loss of uniformity of intersection spacing along the corridor. However, under heavier traffic conditions the results yielded by O-TSCA in Scenarios 2 and 3, while worse than those in Scenario 1, do not differ significantly from one another. It was already known prior to this study that O-TSCA performs better under heavier traffic conditions. This may well be the reason why the PMI-values of the algorithm do not vary much from Scenario 2 to Scenario 3 under heavier traffic conditions. O-TSCA is not suited for use under light traffic conditions, which may be the cause of the worsening results that come with the loss of uniformity in the network spacing.

6 Future work

There are a number of ways in which this work can be taken further. The effectiveness of the three self-organising algorithms considered in this paper may be measured when taking into account a broad range of realistic scenarios. First, a similar experiment may be carried out in the context of a road network consisting of a grid of intersections, rather than merely a corridor roadway. Secondly, pedestrian phases may be incorporated into the signals timings at intersections, which is another way in which to add realism to the simulation model. Finally, the size of the network may be increased in order to observe how the algorithms perform in differently sized road networks.

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