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# A Modified Pressure Model for Max-Pressure Traffic Signal Control

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*Abstract*— **In this paper, we advance the state-of-the-art of Max-Pressure traffic signal control by considering modeling aspect of enhancing the calculation of pressure function.**

**First, we stress out that the conventional pressure model does not consider the distribution of the vehicles between the lanes, and it over-calculates the pressure function when multiplying with the saturation flow of the movement. We conducted a thorough analysis of the existing pressure calculation model. The model's inability to distribute pressure equitably could skew the controller's policy optimization, potentially leading to unfair decisions.**

**Second, the impact of introduced modification is investigated through simulation case studies. The results indicate that the Max-Pressure control policy has been significantly improved. This underlines the importance of accurately characterizing the parameters within the Max-Pressure controller, which is crucial for improved outcomes and more effective decision-making processes.**

## I. INTRODUCTION

Traffic signals are essential components of urban road networks, as they provide a cost-effective strategy to ensure both mobility and safety, while also minimizing costs. A comprehensive survey of existing control strategies is presented in [1], [2]. It has been observed that local control of isolated intersections, without coordination, can lead to sub-optimal network performance. This is because the influence of adjacent intersections is not considered, leading to queue propagation and spill-back effects, which can degrade the overall performance of the control system.

To tackle the problem traffic signal coordination at the network level, centralized control has been proposed, see e.g. [3], [4]. However, such optimal solutions frequently struggle to scale to large networks featuring numerous adjacent intersections. To counteract the scalability issue associated with network control optimization, a decentralized approach was proposed. This paper focuses on one particular decentralized method, the Max-Pressure (MP) algorithm.

The MP algorithm, which was initially devised for packet scheduling in wireless communication networks [5], was later adapted to control traffic signals in urban road networks, [6]. In [6], the MP algorithm applies a decentralized method that determines the optimal solution through activating the phase that holds the maximum difference between upstream and average downstream queues at an intersection, which is called the pressure of the phase. By actuating the maximum pressured phase for a fixed minimum green time, this approach ensures scalability and guarantees stability at a network level, while requiring information on turning ratios and saturation rates to calculate the pressure.

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It should be stressed that the pressures in the original MP controller [6] are computed in accordance with the queues. While [6] led the way in the application of MP for traffic signal control, it does exhibit several limitations.

The first limitation concerns the operation of the algorithm in a *time-step operation* without defining a cycle of phases. This approach could potentially create an unstable phase sequence. To address this, a cycle-step operation approach for the MP algorithm was introduced in several works [7], [8], [9], [10]. The second limitation is tied to the *infinite capacity assumption* of the original MP algorithm, as discussed in [11]. This assumption can result in inefficient decision-making and may trigger a gridlock situation. In response to this, [8] introduced a cycle-step operation and capacity-aware link-based algorithm that takes into account both the first and second limitations.

The effect of the *phase switching gap* or lost time is another limitation of the original MP algorithm, leading to frequent phase switches under heavy traffic conditions. Solutions to this issue were proposed in [9], [12]. Another limitation relates to the neglect of the *spatial distribution of queues* when calculating pressures in the original MP algorithm. This was later addressed in [13].

Lastly, the original MP algorithm could create the *"last packet problem"* under certain extreme scenarios. This situation may cause considerable vehicle delays to a movement due to its lower arrival rate when compared to other movements. This issue was discussed and addressed in [7], [8], [9].

In addition to these, other few variants of the MP algorithm have been proposed, which calculate pressure based on time-oriented variables, instead of queues, such as travel times or delays. This concept, already implemented in wireless communication networks [14], was first applied to traffic signal control in [15]. The work [16] introduced a delay-based signal control with the cycle-step operation, showing promising results from using time-based approach with crowd sourcing data. However, it did not consider the downstream effect. This effect was integrated in [17], which introduced a time-based MP controller that considers upstream and downstream travel times, mirroring the approach of [8] and using the capacity-aware feature in a time-based manner as per [11]. The work [17] provided promising results through real-time field study utilizing data from Bluetooth sensors. Moreover, [18] enhances the algorithm by refining its policy, applying better correlation between the normalizing queue and normalizing travel time, and offers more general lane based approach which can be applied to a larger set of phases. [18] investigates the structure of the cycle based Max-Pressure, instead of offering a fixed cycle time to all intersections, in order to better coordinate between intersections in a grid network, as the phases are updated in a fixed sequence each time step, offering better activation and decision making policy. Later on, a novel time-oriented approach for the Max-Pressure algorithm was introduced in [19], providing a new method for calculating the instant cumulative delay of stopped vehicles. [20] provided a different method by considering the total vehicle delay over time rather than only the last time step delay, improving delay equity for a range of traffic conditions, especially for highly unbalanced traffic flows.

The main goal of this paper is to enhance the pressure calculation model to generalize the Max-Pressure controller, leading to enhancements in the Max-Pressure (MP) control scheme. We consider a limitation, which was not mentioned in the literature: existing MP pressure calculation model is unable to distribute pressure equitably, overlooking the distribution of vehicles between lanes.

The main contributions of this paper are:

- Proposing modifications to the original Max-Pressure control, tackling previously overlooked limitations.
- With the help of simulations, a thorough analyzing and illustrating the sensitivity of the Max-Pressure algorithm's structure and its contribution to achieving superior results.

The rest of this work is structured as follows. In the following section, we introduce the original MP traffic controller and the capacity aware modification. Then, the proposed modifications to the MP traffic controller are presented and analyzed. Afterwards, we offer simulation results analysis and discussion, and lastly, conclude the paper with some insights and suggestions for future research.

## II. MAX-PRESSURE TRAFFIC CONTROLLER BASED ON QUEUE LENGTHS (MP-QL)

In this section, we first present the original queue based MP controller, and then another scheme that addresses the capacity aware is presented.

### A. Original queue based MP controller

The first MP traffic controller [6] is a queue-based approach of a time-step operational algorithm activating the phase with the maximum pressure. The key advantage of the MP controller over other adaptive traffic signal control is its distributed and simple approach, considering the upstream and the downstream queue lengths of each intersection individually, providing a scalable and practical phase actuation. The stability is proved in terms of the expected long-term average of total queues by making simplifying assumptions that the queue length of each turning movement is in a separated lane and the link capacity is infinite. Its implementation requires real-time measurements or estimations of the queue lengths, turning ratios, and saturation flows.

The MP traffic controller utilizes the store-and-forward (SF) model, see e.g. [21], which can capture the dynamic change of the queue lengths at the intersection. Let the queue length $x_{l,m}$ [veh] be defined as the accumulated vehicles in link $l$ with destination $m$ at the beginning of the time step $t$, where $l \in \mathrm{In}_n$ and $m \in \mathrm{Out}_n$. $\mathrm{In}_n$ denotes the set of incoming links of intersection $n$, and $\mathrm{Out}_n$ denotes the set of outgoing links of intersection $n$. Then, the queue length $x_{l,m}(t+1)$ is equal to the current queue length, $x_{l,m}(t)$, subtracting the discharged vehicles and adding the received vehicles plus external demand $d_{l,m}(t+1)$ [veh] during step time $t+1$. This reads as follows, see also Fig. 1,

$$\begin{aligned} x_{l,m}(t+1) =& x_{l,m}(t) - [c_{l,m}(t+1)s_{l,m}(t) \wedge x_{l,m}(t)] + \\ & \sum_k [c_{k,l}(t+1)s_{k,l}(t) \wedge x_{k,l}(t)] r_{l,m}(t+1) \\ & + d_{l,m}(t+1)\,, \end{aligned} \tag{1}$$

where $c_{l,m}(t+1)$ [veh] is the saturation flow (service rate), i.e. the maximum vehicles that can discharge from link $l$ to link $m$ if $s_{l,m}(t)$ is equal to 1; $s_{l,m}(t)$ is an indicator of movement actuation, i.e. $s_{l,m}(t) = 1$ if the movement is actuated and 0 otherwise; $r_{l,m}(t+1)$ is the turning ratio, i.e. the proportion of vehicles that are accumulated at link $l$ with destination $m$; and $k \in \mathrm{In}_{n-1}$. The operator $A \wedge B = \min[A, B]$. Note that indices $n-1$ and $n+1$ represent prior and subsequent intersections to intersection $n$, respectively.

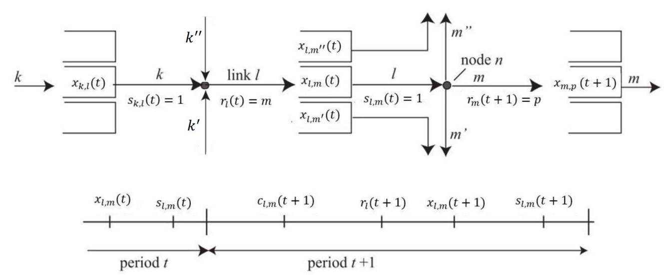


Fig. 1. The queuing network (top) and the sequence of events in each period (bottom), based on [6].

The MP traffic controller, as introduced in [6], actuates the maximum pressured phase each time step $t$ at each intersection. The MP control policy $u^*(t) : x \to s$;

$$u^*(t) = \mathrm{argmax}\{P_s(t) | s \in \mathrm{S}_n\}\,, \tag{2}$$

where $\mathrm{S}_n$ is the set of all phases of intersection $n$. The pressure of phase $s$ at intersection $n$ is calculated as:

$$\begin{aligned} P_s(t) &= \sum_{(l,m)} w_{l,m}(t)c_{l,m}(t)s_{l,m}(t) \\ &= \sum_{(l,m):s_{l,m}=1} w_{l,m}(t)c_{l,m}(t)\,, \qquad \forall s \in \mathrm{S}_n\,. \end{aligned} \tag{3}$$

In other words, the pressure of each phase is the sum of each movement's weight multiplied by its saturation flow. The weight of the movement from link $l$ to $m$ during time step $t$, $w_{l,m}(t)$, is calculated as the queue length of the movement

$x_{l,m}(t)$ minus the average queue length $\sum_p r_{m,p}(t)x_{m,p}(t)$ at the output links, i.e.

$$w_{l,m}(t) = x_{l,m}(t) - \sum_p r_{m,p}(t)x_{m,p}(t)\,, \quad \forall p \in \mathrm{Out}_{n+1}\,. \tag{4}$$

If we regard $\sum_p r_{m,p}(t)x_{m,p}(t)$ as the average downstream queue length and $x_{l,m}$ as the upstream queue length, then $w_{l,m}(t)$ is simply the difference between the upstream and the downstream queue lengths.

### B. Capacity aware queue based MP controller

In [11], a modified scheme of the MP algorithm is developed, which considers the limited capacities of the links. The modified scheme showed that relaxing the infinite link capacity assumption is sensitive as link capacities can limit the stability guarantee and cause the network entering a gridlock state due to the loss of conservation and congestion propagation. It was noted in [11] that the capacity aware of the movement should be considered during over-saturated conditions, however, during under-saturated conditions, given the fact that queues do not reach the link capacities, the infinite link capacity assumption introduced by [6] is valid and the Max-Pressure control and its stability guarantee are recovered. Hence, following this note, we present a simplified version of the weights of the movements presented in [11], which still considers the capacity aware during congestion, as follows:

$$w_{l,m}(t) = \begin{cases} \frac{x_{l,m}(t)}{x_{\max,l,m}} - \sum_p r_{m,p} \frac{x_{m,p}(t)}{x_{\max,m,p}} & \text{OverSat} \\ x_{l,m} - \sum_p r_{m,p}\ x_{m,p}(t)(t) & \text{UnderSat} \end{cases} \tag{5}$$

$\forall m \in \mathrm{Out}_n$, $p \in \mathrm{Out}_{n+1}$, $l \in \mathrm{In}_n$; where $w_{l,m}(t)$ is the weight associated to the movement from the link $l$ to link $m$, $x_{l,m}(t)$ [veh] is the number of vehicles at the link $l$ that aim to depart to link $m$ during the cycle $t$, and $x_{\max,l,m}(t)$ [veh] is the maximum capacity of queuing vehicles in the link $l$ with destination to link $m$. In other words, the weight of the movement from link $l$ to link $m$ at cycle $t$, $w_{l,m}(t)$, is calculated as the normalized queue length at link $l$ minus the average normalized queue length at the output links. It should be stressed that (5) and (3) consider the case of movements (at upstream or downstream) *without a shared lane*. When a lane shares different movements, it is difficult to estimate the destination of the vehicles.

## III. Max-Pressure traffic controller modification

We will introduce modifications to the Max-Pressure algorithm, prescribed in the previous section, i.e. modifying the pressure calculation function for the queuing model.

### A. Pressure calculation model modification

In essence, the original pressure calculation model of each phase (see (3)) is the sum of all product of the phase's movements weight $w_{l,m}(t)$ at time step $t$ and its saturation flow $c_{l,m}(t)$. However, some issues are raised when considering the weight and saturation flow independently. The multiplication by the saturation flow acts as a parameter that prioritizes movements based on their saturation rates, instead of the weights calculated from the state of the movements.

To rectify this, we propose a modification to the equation that takes the number of lanes of a specific movement into account. Specifically, we suggest dividing the saturation flow of each movement by the number of lanes for that movement. Hence, the pressure equation is modified as follows

$$P_s(t) = \sum_{(l,m):s_{l,m}=1} w_{l,m}(t)\frac{c_{l,m}(t)}{n_{l,m}}\,, \qquad \forall s \in \mathrm{S}_n\,, \tag{6}$$

where $n_{l,m}$ is the number of lanes for vehicles traveling from link $l$ to link $m$. This adjustment facilitates a fairer comparison among movements by effectively multiplying the weight of each lane in a movement by its saturation flow. Thus, it does not only take into account the volume of vehicles in a movement but also the number of lanes that are being utilized, providing a more equitable view of the system's operation.

Furthermore, the computation of weights is done based purely on the number of vehicles in each movement, without factoring in the specific arrangement of vehicles within the lanes of a given movement. This oversight could result in green idling and lead to erroneous decision-making. Consequently, we propose that the calculation of weighted pressure should also be normalized by the number of lanes in the movement. This can be formulated as:

$$P_s(t) = \sum_{(l,m):s_{l,m}=1} \frac{w_{l,m}(t)}{n_{l,m}} \cdot \frac{c_{l,m}(t)}{n_{l,m}}, \quad \forall s \in \mathrm{S}_n\,. \tag{7}$$

In the approach of queue-based capacity awareness, the number of vehicles is normalized over the maximum link capacity of the movement (sum of lane capacities), i.e. this approach does not consider the capacity of each individual lane within the movement, but rather accumulates the maximum capacities of all lanes involved. As a result, we propose a modification to the weighted pressure function introduced in (5) to address this issue, as follows

$$w^*_{l,m}(t) = \frac{x_{l,m}(t)}{x_{\max,l,m}/n_{l,m}} - \sum_p r_{m,p}(t)\frac{x_{m,p}(t)}{x_{\max,m,p}/n_{m,p}}\,, \tag{8}$$

$\forall p \in \mathrm{Out}_{n+1}$; where $w^*_{l,m}(t)$ is the modified weight associated to the movement from link $l$ to link $m$ to accommodate the lane normalization of the saturation flow, $x_{l,m}(t)$ [veh] is the number of vehicles at the link $l$ and departing to link $m$ during the time step $t$, $x_{\max,l,m}(t)$ [veh] is the maximum capacity of queuing vehicles in the link $l$ to link $m$, and $n_{l,m}$ is the number of lanes for vehicles traveling from link $l$ to link $m$.

The Max-Pressure algorithm is a finely tuned structure, where inaccurate parameters could significantly influence decision-making outcomes. This underscores the importance of accurately defining the pressure and weights, whilst ensuring the stability guarantee remains unaffected.

### B. An illustration example for the modification

An illustration example is given to analyze the effect of the modification. Let us consider intersection $n$ which has 4 phases that can be activated. The original pressure model (O-MP), see (3), is compared with normalizing the saturation flow pressure model (CN-MP), see (6), and over normalizing saturation flow and the weight (WNCN-MP), see (7). In phase 1, there are 5 vehicles which aim to travel from link $l$ to link $m$, while in phase 2 there are 5 vehicles which aim to travel from link $l''$ to link $m'''$. We assume that the saturation flow for each turning left lane and straight lane is the same, and equals to $0.5$ $[\mathrm{veh}/(\mathrm{lane} \cdot \mathrm{sec})]$. Then, one gets that the saturation flow for vehicles departing from link $l$ to link $m$ is $c_{l,m} = 1\,[\mathrm{veh}/\mathrm{sec}]$, and the time step of Max-Pressure controller is $T = 10\,[\mathrm{sec}]$, see Fig. 2.

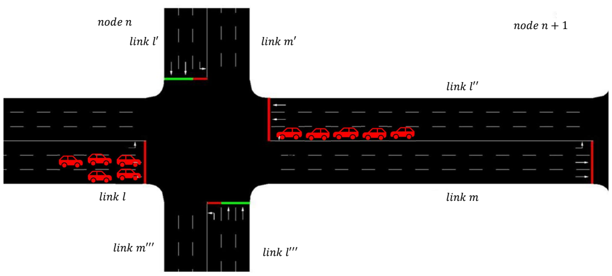



Fig. 2. An illustration example: comparison between the O-MP, CN-MP, and WNCN-MP controllers.

| | Pressure calculation models | | |
|---|---|---|---|
| Time | O-MP | CN-MP | WNCN-MP |
| $t_0$ | $P_1 = 5, P_2 = 2.5$ | $P_1 = 2.5, P_2 = 2.5$ | $P_1 = 1.25, P_2 = 2.5$ |

TABLE I
CALCULATION OF MAX-PRESSURE ALGORITHM WEIGHT FOR O-MP, CN-MP, AND WNCN-MP.

Table I shows the difference between the pressure calculations. Firstly, the O-MP shows that although phase 1 and phase 4 hold the same number of vehicles, yet because phase 1 has 2 lanes of the same movement its effect two times as much. The CN-MP strategy seems to be more logical because its comparison between movements is fair. But in this example, it is shown that there is no difference between the pressure values, and activating phase 1 or phase 4 would have the same effect on the intersection state. As one can see from Fig. 2, if every time step activated 5 $[\mathrm{veh}/(\mathrm{lane} \cdot 10\mathrm{sec})]$ can depart, then activating phase 1 would manage to empty the queue within the first 5 seconds and we have 5 seconds green idling, that why the WNCN-MP would be the most preferred one. It clearly shows that at this specific time step it is preferred to activate phase 4 over phase 1.

## IV. SIMULATION-BASED RESULTS

In this section, we present the simulation results comparing the existing MP controller schemes with the proposed modifications. The performance of various MP controller hypotheses and parameters will be tested through different case studies and sensitivity analysis.

*Original MP Controller Scheme without Capacity Aware*

We consider three variants of the original Max-Pressure controller pressure model:

- (O-MP) Original Max-Pressure controller pressure model.
- (CN-MP) Saturation flow modification only, as shown in (6).
- (WNCN-MP) Both movement weights and saturation flows are modified, as shown in (7).

*Original MP Controller Scheme with Capacity Aware*

We explore four configurations of the original MP controller with capacity-aware modifications:

- (O-MP) Original Max-Pressure controller pressure model.
- (CN-MP) Saturation flow modification only, as shown in (6).
- ($W^*CN$) Lane capacity aware and saturation flow modifications, as shown in (8) and (6).
- ($W^*NCN$) All lane capacity aware, movement weights, and saturation flow modifications as shown in (8) and (7).

*Simulation setup*

All the models are activated in an a-cyclic manner and updated at each time step. The comparison is performed using microscopic simulations in SUMO [22]. Our use cases model an urban signalized network with signalized intersections, without considering any cycle length or a prefixed sequence for each intersection. The minimum green time for each phase is $g_{\min}$ [s], the time gap is 2 [s], and the yellow signal lasts 3 [s]. The phases are presented in Fig. 3.

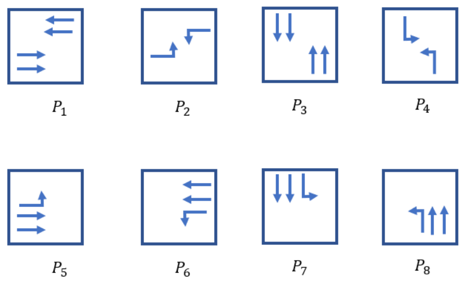
In the following, *two case studies* are considered. We will conduct two case studies to present a fair comparison to existing MP approaches (with and without capacity awareness) with a stable exogenous demand to each case. The case studies are:

*Use Case 1: 5x5 Grid Network* $400[m] \times 400[m]$*:* In this case study, we compare with the original MP controller without capacity awareness on a $5x5$ grid network measuring $400[m] \times 400[m]$. The demand profile at an average intersection is shown in Fig. 4(a).

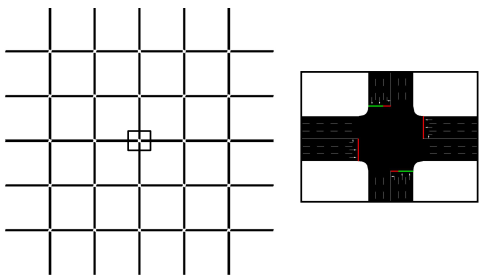
*Use Case 2: 5x5 Grid Network* $100[m] \times 100[m]$*:* This case study involves comparing the original MP controller with capacity awareness on a smaller $5x5$ grid network measuring $100[m] \times 100[m]$. The demand profile at an average intersection is shown in Fig. 4(b).

### A. Use case 1 – a $5x5$ grid network $400[m]x400[m]$

We consider a 5X5 homogeneous grid network, where the length of each link between intersections is 400 [m], each intersection has 4 links with 3 lanes at upstream and downstream, containing 4 approach phases that each consists

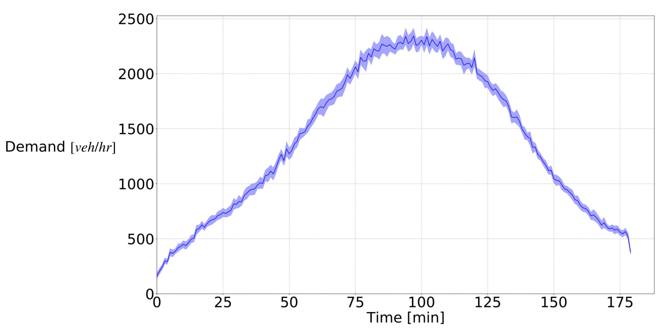



(a)

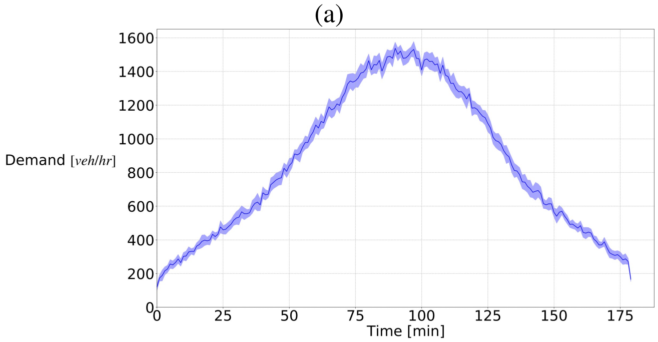


(b)

Fig. 3. (a) Phase structure at intersections; (b) 5X5 Grid Network.




(a)




(b)

Fig. 4. Demand profile at an average intersection: (i) use case $5x5$ grid network $400[m]$ x $400[m]$ (Demand fig (a)); and (ii) use case $5x5$ grid network $100[m]$ x $100[m]$ (Demand fig (b)).

of left and two through movements. The MP algorithms are examined under different parameters that are being tested, through 16 replications, under demand profile in Fig. 4(a).

In this case study simulation, we aim to test the hypothesis that the pressure calculation, as described in (7), is extremely important to improve decision making of the controller. The performance sensitivity analyses of different pressure models (O-MP, CN-MP, WNCN-MP) are shown for: (a) standard deviation vs. mean of travel time in Fig. 5, (b) standard deviation vs. average delay per intersection in Fig. 6, and (c) standard deviation vs. average queue per intersection in Fig. 7. Downstream turning ratio with fixed frequency $f = 15\,[\text{min}]$ and fixed time step $g = 13, .., 16\,[\text{s}]$ are also presented.

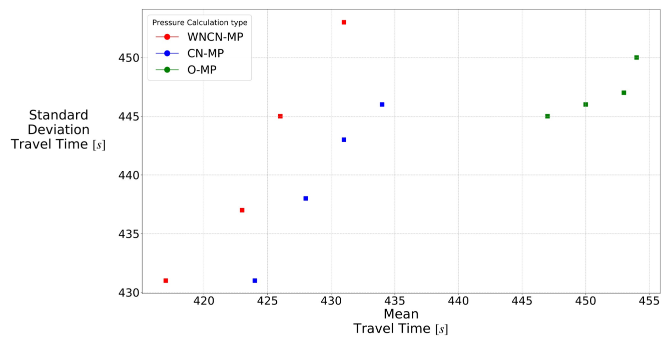



Fig. 5. Use case 1 ($5x5$ grid network $400[m]$ x $400[m]$) – performance sensitivity analysis of different pressure models (O-MP, CN-MP, WNCN-MP): standard deviation vs. mean of travel time for downstream turning ratio fixed frequency $f = 15\,[\text{min}]$ and fixed time step $g = 13, .., 16\,[\text{s}]$.

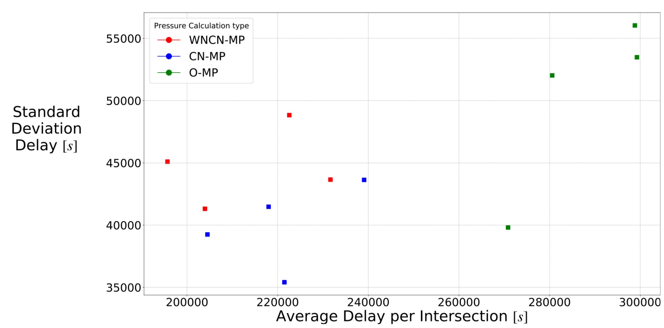



Fig. 6. Use case 1 ($5x5$ grid network $400[m]$ x $400[m]$) – performance sensitivity analysis of different pressure models (O-MP, CN-MP, WNCN-MP): standard deviation vs. average delay per intersection for downstream turning ratios fixed frequency $f = 15\,[\text{min}]$ and fixed time step $g = 13, .., 16\,[\text{s}]$.

Insight can be drawn from Fig. 5, which illustrates the performance of different Max-Pressure control algorithms. The original Max-Pressure algorithm (O-MP) exhibits inadequate decision-making due to an imprecise pressure model. This deficiency stems from the algorithm's tendency to prioritize movements based on their saturation flows. Given that the straight movement's saturation flow is twice that of the left, the left-turn flow eventually becomes larger, leading the controller to lose its optimization.

When considering the movement-based Max-Pressure control pressure calculation models CN-MP and WNCN-MP,

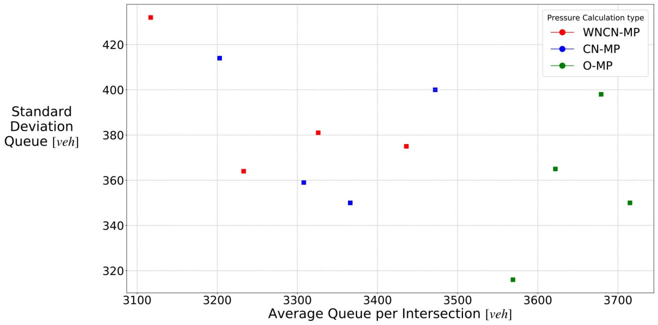



Fig. 7. Use case 1 ($5x5$ grid network $400[m]$ x $400[m]$) – performance sensitivity analysis of different pressure models (O-MP, CN-MP, WNCN-MP): standard deviation vs. average queue per intersection for downstream turning ratios with fixed frequency $f = 15\,[\text{min}]$ and fixed time step $g = 13, .., 16\,[\text{s}]$.

the results demonstrate significant improvement. Here, movements are treated as individual lanes, eliminating the preference between left and straight turns, and thus improving the performance, see Figs. 5, 6, 7. Moreover, on average at all pressure calculation models, we can see from the figures that M-DTR shows better performance than O-DTR, specially at the CN-MP pressure calculation.

The weighted control Max-Pressure model, WNCN-MP, enhances vehicle allocation within the lane movements. In this case study, as shown in the figures, there is a slight difference between the results of CN-MP and WNCN-MP pressure calculation models. In the next case study, use case 2, there is a substantial improvement when the demand is close to the maximum capacity flow. This refinement effectively minimizes the green idling phenomena, thereby delivering superior results. This enhancement underscores the impact of considering both lane and movement dynamics in improving the effectiveness of traffic signal control algorithms.

*1) Comparison between the original and modified MP controllers:* In order to assess the effectiveness of our proposed modification models, we conduct simulations and compare their performance with the original Max-Pressure models. Our goal is to demonstrate that effectiveness of defining the parameters to improve traffic flow in traffic networks. Hence, the original Max-Pressure algorithm (Original-MP) utilizes the best results obtained from the original pressure calculation model (O-MP); and the modified Max-Pressure algorithm (Modified-MP) utilizes the best results obtained from the modified pressure calculation model (WNCN-MP). The results in Fig. 8 clearly show that the importance of parameter design on the MP controller. Significant improvements are obtained with the Modified-MP compared with Original-MP over all metrics - maximum queues and accumulated delays, and the average delay per vehicle at an average intersection.

### *B. Use case 2 – $5x5$ grid network $100[m]x100[m]$*

In this case, we consider a similar network of the previous case, i.e. a 5X5 homogeneous grid network, but the length of each link between intersections is 100 [m]. The MP algorithms are examined under different parameters that are

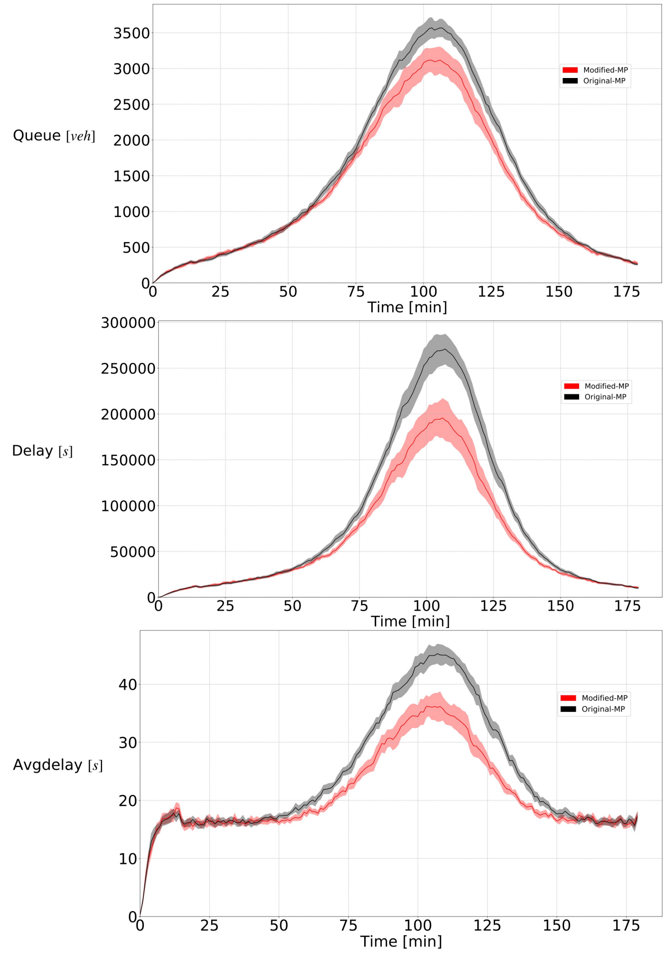



Fig. 8. Use case 1 ($5x5$ grid network $400[m]$ x $400[m]$) – obtained results for the original MP and modified MP controllers: (a) accumulated queues, (b) accumulated delays, and (c) average delay per vehicle over simulation time.

being tested, through 16 replications, under demand profile in Fig. 4(b).

*1) The pressure calculation model analysis:* In this case study simulation, we aim to test the pressure calculation models, as described in (6) and (7), but now with limited capacity aware. We will compare implementing the modification of the weighted lane capacity mentioned in (8), showing the need to fix the weighted capacity parameter when updating the saturation flow.

Insight can be drawn from Fig. 9, which illustrates the performance of different Max-Pressure control algorithms. The proposed update of pressure calculation ($W^{*}NCN-MP$) shows superior performance at all metrics at different turning ratios, where the algorithm managed to reach delays and queue far less than any other algorithm. Although the original algorithm is stable and provides sufficient results, the proposed modification still reaches better results.

Moreover, when normalization the movement-based Max-Pressure control algorithm with capacity aware (CN-MP), the results demonstrate significant improvement. When modifying also the lane capacity aware ($W^{*}CN-MP$), movements

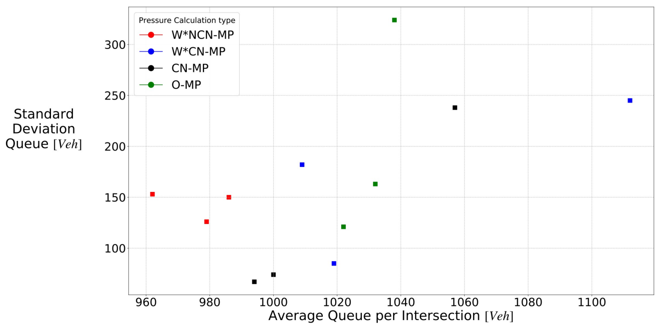



Fig. 9. Use case 2 ($5x5$ grid network $100[m]$ x $100[m]$) – performance sensitivity analysis of different pressure models: standard deviation vs. mean of travel time for downstream turning ratios with frequencies $f = 30, 45, 60\,[\text{min}]$ and fixed time step $g = 11\,[\text{s}]$.

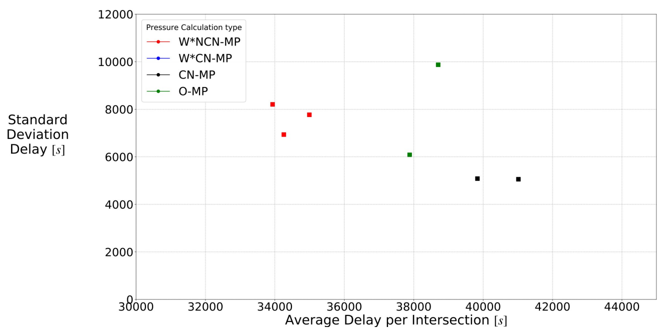



Fig. 10. Use case 2 ($5x5$ grid network $100[m]$ x $100[m]$) – performance sensitivity analysis of different pressure models: standard deviation vs. average delay per intersection for downstream turning ratios with frequencies $f = 30, 45, 60\,[\text{min}]$ and fixed time step $g = 11\,[\text{s}]$.

are treated as individual lanes, reaching better results. When normalizing the weight parameter at the pressure function, see (7), the algorithm can reach much more stable and optimal results.

*2) Comparison of the original Max-Pressure model and modified version:* In order to assess the effectiveness of our proposed modification models, we will conduct simulations and compare their performance with the original Max-Pressure models. Our aim is to demonstrate that effectiveness of defining the parameters to improving traffic flow in traffic networks. Hence, the original Max-Pressure algorithm (Original-MP) utilizes the best results obtained from the original pressure calculation model (O-MP); and the modified Max-Pressure algorithm (Modified-MP) utilizes the best results obtained from the modified pressure calculation model ($W^{*}NCN-MP$).

The importance of parameter design on the Max-Pressure controller is clearly demonstrated, as Fig. 12 shows $5-10\%$ improvements in the maximum accumulated delays and queues and the average delay per vehicle at each average intersection. Since, the best performance of the modified version was at turning ratio update frequency $f = 45\,[\text{min}]$ and the original MP at $f = 45\,[\text{min}]$, one can clearly see an immediate drop after updating the first turning ratio to adapt to the simulation dynamic demand, which further supports the strategy of not predefining the turning ratio in advance,

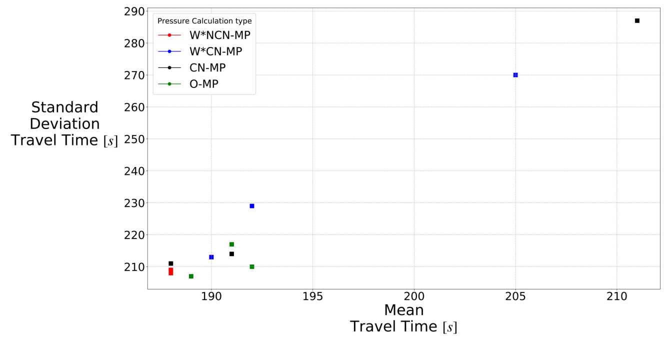



Fig. 11. Use case 2 ($5x5$ grid network $100[m]$ x $100[m]$) – performance sensitivity analysis of different pressure models: standard deviation vs. average queue per intersection for downstream turning ratios with frequencies $f = 30, 45, 60\,[\text{min}]$ and fixed time step $g = 11\,[\text{s}]$.

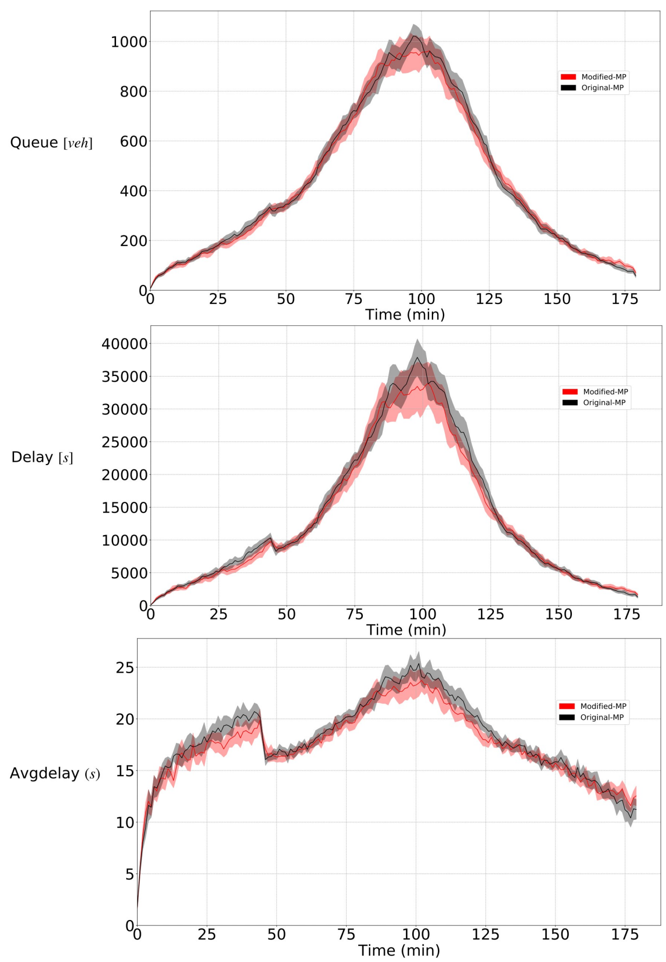



Fig. 12. Use case 2 ($5x5$ grid network $100[m]$ x $100[m]$) – obtained results for the original MP and modified MP controllers: (a) accumulated queues, (b) accumulated delays, and (c) average delay per vehicle over simulation time.

but rather it can be updated through online demand.

## V. Conclusion and Future Research

In this study, we propose a modification to the Max-Pressure model that focuses on the importance in accurately prescribing the parameters of the Max-Pressure algorithm in the literature, without affecting the stability guarantee property. We evaluated the performance of modified models through extensive simulations on complex traffic networks, and compared them with existing Max-Pressure algorithms. Our results demonstrate the importance of the modifications as the proposed model outperforms the existing algorithm in all metrics, especially in stabilizing the accumulated delay of vehicles, even under high-demand and complex network conditions.

While these findings are encouraging, they also raise new questions and create new challenges for future research in the max pressure research. One potential area of exploration is the application of these modifications to other Max-Pressure traffic signal control strategies, i.e. time based Max-Pressure models. Further, it would be interesting to investigate the extent to which these modifications could be applicable in real-world scenarios, beyond the simulations we conducted.

It is also worth exploring whether the modified algorithm can maintain its superior performance in even more complex traffic scenarios, such as those including heterogeneous networks and demand. We envision that such investigations could highlight further the importance of the introduced modifications to the Max-Pressure literature.

Finally, we believe that these potential areas of study can significantly contribute to the ongoing evolution of the Max-Pressure algorithm and its broader applications in traffic control.

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