Priority Pass: Signal Control with Focus on Needs

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Abstract

Signalized intersection management is typically designed with a focus on transportation efficiency metrics such as throughput, queue length and average delay time, to the neglect of vehicle-specific urgencies. This conceptual work proposes a Priority Pass for urban networks as a feasible, economic instrument to expedite entitled vehicles at auction-controlled signalized intersections using movement-phase bidders. The interplay of transportation and economic efficiency at intersections with varying saturation, symmetry, and entitlement is analyzed. The value of the concept is robustly demonstrated for a wide range of scenarios. The Priority Pass creates significant benefits for entitled vehicles without causing arbitrary delays for not-entitled vehicles or de trop worsening transportation efficiency. What's more, no significant conflict between transportation and economic efficiency was found in the given setup.

Keywords

Transport and society; Traffic engineering; Transport economics; signalized intersection control; auctions; value of time (VOT)

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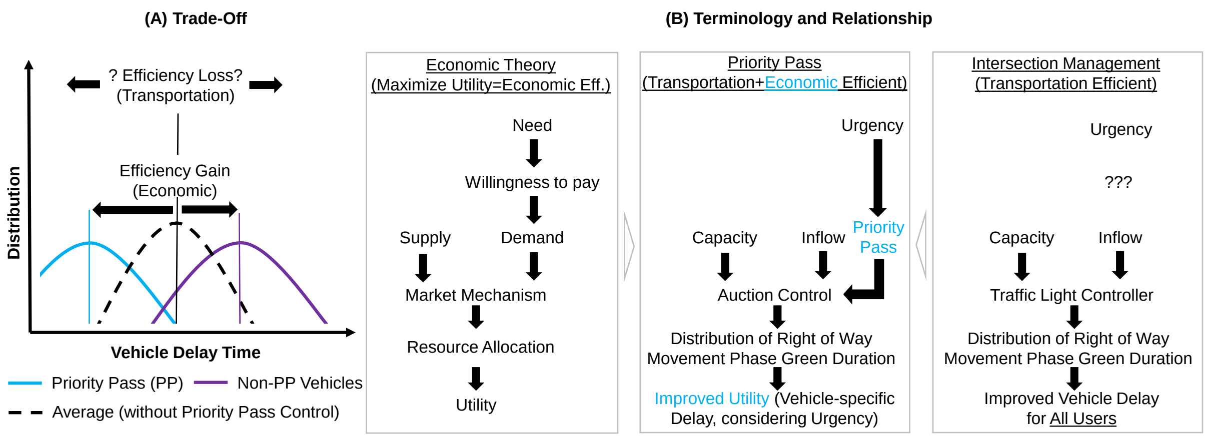
1 Introduction

Intersections are the central bottleneck of the urban mobility infrastructure. Congestion occurs, when the demand (traffic inflow) exceeds the supply (intersection capacity). A growing branch of literature applies market mechanisms in the field of intersection management (Iliopoulou *et al.* (2022)). Auction markets are particularly interesting to study, because they represent distributed control algorithms and allow for the inclusion of vehicle-specific preferences (needs) into the control strategy. Previous works in the field of auction-controlled signalized intersection management consider either the next green phase or the duration of green phases in a fixed-cycle as a resource, and either vehicles or movement-phases as auction participants (Carlino *et al.* (2013)). While most studies focus on transportation-specific, global efficiency metrics such as throughput and average delay time, little attention was spent on vehicle-subjective need considerations.

Isukapati and Smith (2017) and Lin and Jabari (2021) study auctions with connected-vehicle-agents that take their subjective value of time into consideration when bidding for the right-of-way at an intersection. These studies indicate the possibility of expediting needy users without causing arbitrary delays to others. However, the proposed auctions require intelligent transportation systems with connected vehicles, a costly communication overhead, and a decision-making process at every intersection.

This conceptual study sets out to investigate a more feasible approach to need-based signalized intersection management: the priority pass (outlined in Fig.1). Entitled vehicles granted with the priority pass, shall be expedited at intersections resulting in significantly lower delays. The Priority Pass could be registered online for a specific period, and integrated with existing, vehicle identification infrastructure, such as tolled freeway lanes and urban congestion pricing. Hence, this concept facilitates immediate implementation. What's more, this concept facilitates agents' decision-making process by transferring from decisions at intersections to decisions for specific periods (e.g. hours or days).

Figure 1: Concept Study: Priority Pass



Similar to freeway tolls, high occupancy toll lanes, airport priority lines, and congestion pricing, this concept includes needs-consideration in traffic management and offers another modality to trade-off time and money by expressing value-of-time as a willingness to pay. Contrary to intersection control that solely focuses on transportation efficiency, the Priority Pass creates a link between the need (urgency) and the market mechanism. Economic instruments describe road transportation systems as market mechanisms that allocate spatio-temporal resources, and aim to control demand (e.g. tolled freeway lanes, urban congestion pricing) and supply (e.g. perimeter control, tradeable mobility permits). Efficient (optimal) resource allocation describes the utility-maximizing distribution of resources to a population. Utility is the measure for fulfillment of needs. Need is the subjective perception of shortage and the willingness to overcome that state. In transportation economics, need is mostly manifested in urgency, a temporal preference of shorter over longer times (e.g. travel time, delay time). Subjects trade-off their needs and translate their subjective urgency to a willingness to pay, which is then aggregated to a market demand that meets a market supply.

This work explores the effect of the Priority Pass on transportation and economic efficiency of auction-controlled signalized intersections for varying levels of saturation, symmetry, and entitlement. Moreover, the trade-off between transportation & economic efficiency, and between advantaging entitled & disadvantaging not entitled vehicles is described.

We contribute to the literature...

- on auction-controlled signalized intersections by...
  - providing a feasible mean of integrating value-of-time
  - combining movement-phase auctions for intersections with spatially and temporally separated vehicle auctions for specific periods in time
- on economic instruments in traffic management by...
  - proposing an economic instrument that does not address the control of demand and supply, but that paraphrases a market mechanism achieving higher levels of economic efficiency (utility) by linking need (urgency) to the control.

2 Methodology

This study employs a signalized intersection control algorithm based on movement-phase bidding auctions with the next green phase being the resource. The auctions are triggered for two reasons: (i) at regular intervals t_{auc}, after the minimal green period duration $t_{\min}$ since the last transition; (ii) if the current phase's green period duration exceeds the maximum green period duration $t_{\max}$ (all phases except for the current can bid and win). We consider $t_{\max}$ exemplary at 120 seconds. The transition from one phase's green period to another phase takes place via an intermediate, yellow signal, that takes 3 seconds (security consideration) to announce the end of the current green period. If the auction winning phase equals the current, green movement-phase, no transition period takes place.

We consider a sealed bid, first price, single item auction, where the bid $\widehat{b}_p$ of phase p equals the sum of two components: conventional bids b_p and the Priority Pass bids b_p^{pp} (number of entitled vehicles). The threshold τ represents the focus of this control mechanism on prioritizing entitled vehicles.

$$\widehat{b}_p = (1-\tau)b_p + (\tau)b_p^{pp} \;,\; \tau \in [0;1] \tag{1}$$

We consider two types of conventional bids b_p: queue length (Carlino *et al.* (2013)) and vehicle-position-weighted-sum of vehicles (Covell *et al.* (2015); Baluja *et al.* (2017); Iio *et al.* (2019)). While in the first bidding scheme each vehicle is counted as one, in the second bidding scheme, each vehicle is counted with a weight w_k depending on which road-segment k it is located on. We consider following road segments (measured in meters before intersection): [<10, 10-20, 20-30, 30-40, 40-50, >50].

$$b_{p,1} = n_p \tag{2}$$

$$b_{p,2} = \sum_{v_p} w_k k(v_p) \tag{3}$$

We compare the Priority Pass concept with a fixed-cycle-control, and auctions with movement-phase bidders ($\tau = 0$). All algorithm parameters (green phase duration for fixed-cycle, t_{min}, t_{auc}, and weights for phase-auctions) are optimized for a given traffic flow using the Next-Ascent Stochastic Hillclimbing (NASH) algorithm Baluja (2017). The sum of average and standard deviation of the vehicle delay is used as the cost function.

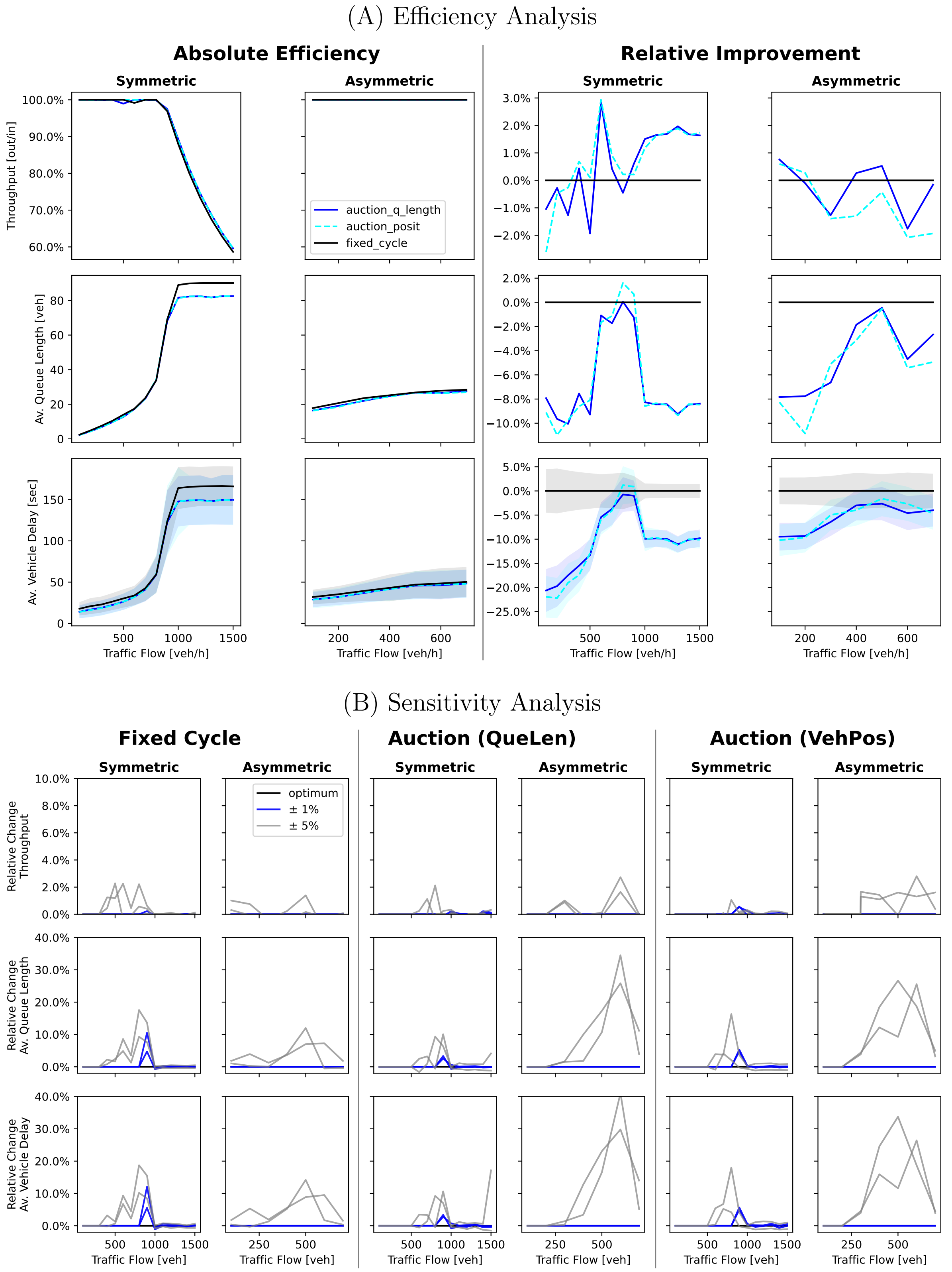
For simulation, we use the time discrete (one second steps) and space continuous microscopic traffic simulation environment SUMO Krajzewicz *et al.* (2012); we use the standard settings for vehicles, and urban lanes with speed limitations of 13.89 m/sec. For every entrance lane to the network around the intersection and for every second, a vehicle is generated if a random number exceeds a threshold $\alpha \in [0; 1]$. The route of the generated vehicle is randomly chosen from a uniform distribution across all shortest-routes connecting to the exit lanes. Vehicles are randomly entitled with the Priority Pass using a random number that exceeds a threshold $1 - \gamma$ where γ is the entitled share of the population. In each simulation, traffic generation is starting from the beginning, while the recording starts ten minutes later; after 70 minutes (60 minutes of recording) the simulation ends. Each experiment is repeated in 10 simulations; average and standard deviation of recorded performance metrics are calculated accordingly. The network used consists of one intersection that is the crossing of two 500m long, single-sided lanes (north-south, and east-west). We assume that vehicles on movement-phase lanes are detected by intersection sensors at a distance smaller or equal to 100m. This simple network is sufficient to study the effect of the Priority Pass on the intersection control performance and the potential benefits for entitled vehicles in both, symmetric ([100, 200, ..., 1500] vehicles per lane) and asymmetric (1500 vehicles for both lanes, [(100, 1400), (200, 1300), ..., (700, 800)]) traffic flow scenarios.

3 Results and discussion

The transportation efficiency for the parameter-optimized benchmark control algorithms is depicted in Fig. 2(A) (shades around graphs represent one standard deviation). The largest absolute efficiency improvements of the actuated (auction) control over the fixed-cycle algorithm in the symmetric scenarios appear after the transgression of the intersection capacity at around 1000 vehicles per lane. In the asymmetric scenarios smaller absolute efficiency improvements can be observed, and the efficiency is at a level similar to the symmetric scenario with a similar traffic flow. The inspection of relative efficiency for both scenario groups reveals that huge efficiency improvements can be gained for metrics such as the average queue length (up to 10%) and the average vehicle delay (up to 20%), while the throughput is affected only a little by around 2%. The efficiency levels of auctions based on the vehicle positions are only slightly better than those based on queue lengths.

A parameter-sensitivity analysis was conducted by assessing efficiency at 1% and 5% deviation from optimal parameters, in order to evaluate the robustness of the control algorithms; its results are shown in Fig. 2(B)). As all time related parameters where modeled as integer values, and lay at low levels for very low traffic volumes (below 300 vehicles per lane), their variation results in almost insignificant efficiency changes. The fixed-cycle control has low efficiency losses when varying the cycle phase durations, compared to the variation of auction based control parameters. For all controllers and scenarios, one can observe that the throughput metric is not affected too much, while queue length, and especially average vehicle delay suffer most from sub-optimal parameterization.

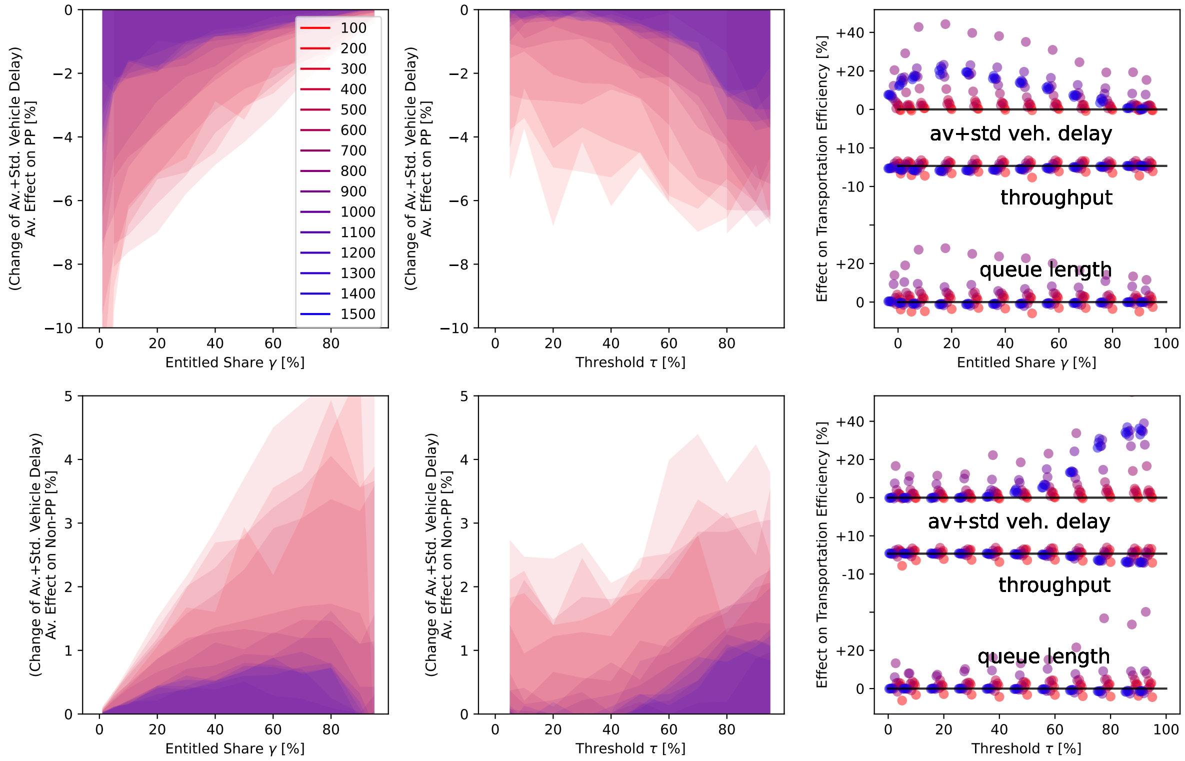
Figure 2: Benchmark Signalized Control Algorithms



Please note, that the following figures exhibit the results for intersection controllers based on auctions with queue lengths; similar results can be observed for the results with auctions using vehicle positions.

The effect of a Priority Pass on auction based intersection controllers for symmetric scenarios is outlined in Fig. 3 (similar results were found for asymmetric scenarios). The two hyper-parameters γ and τ were varied, and the effect on average delay time was compared for Priority Pass entitled vehicles (PP) and not entitled vehicles (non-PP). The different colors shading between red and blue represent the different traffic flow volumes per lane. The first column of figures shows the variation of entitlement share γ, the second column of figures shows the variation of control threshold τ, and the third column analyses the sensitivity of transportation efficiency. One can observe that by prioritizing entitled vehicles and generating benefits (reduced delay time) for entitled vehicles, one causes additional delay time for non-entitled vehicles. The strength of this effect depends on the parameters τ & γ and the traffic flow. Low shares of entitled vehicles result in small damages to non-PP and great benefits for PP. The benefits for PP diminish with increasing shares, while the damages to non-PP increase strongly. This relationship is strong in low traffic scenarios (below saturation) with around 5 seconds of delay change, while it is weak in high traffic scenarios (above saturation) with less than one second of delay change. The control threshold increases the gap between the benefits of PP and the damages of non-PP. This relationship is stronger for lower traffic volumes (below saturation). The sensitivity of transportation efficiency to the Priority Pass is low (around 4%) for the throughput metric, mediocre for the queue length metric (around 10%) and high on the average vehicle delay (around 20%) The sensitivity is stronger for over-saturated traffic flows and negligibly low for under-saturated scenarios. These findings match the previous implications of the sensitivity analysis of the benchmark controllers.

Figure 3: Effects of Priority Pass Control



A trade-off between the advantagement of entitled vehicles versus the disadvantagement of not-entitled vehicles for symmetric and asymmetric scenarios with a queue length based controller is shown in Fig. 4. The described relationships of entitlement share γ and threshold τ on the gap between PP and non PP can be rediscovered in the first two figures from the left. The different colors reveal the effect of traffic flow on relationship strength for the symmetric scenario. The asymmetry has a smaller impact on the discussed relationships when compared with variation of volume. The trade-off curves and optimal Priority Pass parameters lie in a region very similar to the symmetric case with similar traffic conditions.

The right figure summarizes the trade-off as heatmap; the darker the color, the greater the economic benefit. The heatmap reveals, that the benefits of the Priority Pass are low for high τ and low γ. Benefit-maximizing hyper parameter combinations for each scenario are displayed as a colored point. We measure the economic benefit $\mathcal{B}$ (€) as average reduced cost from the situation without C and with a Priority Pass C_{pp}:

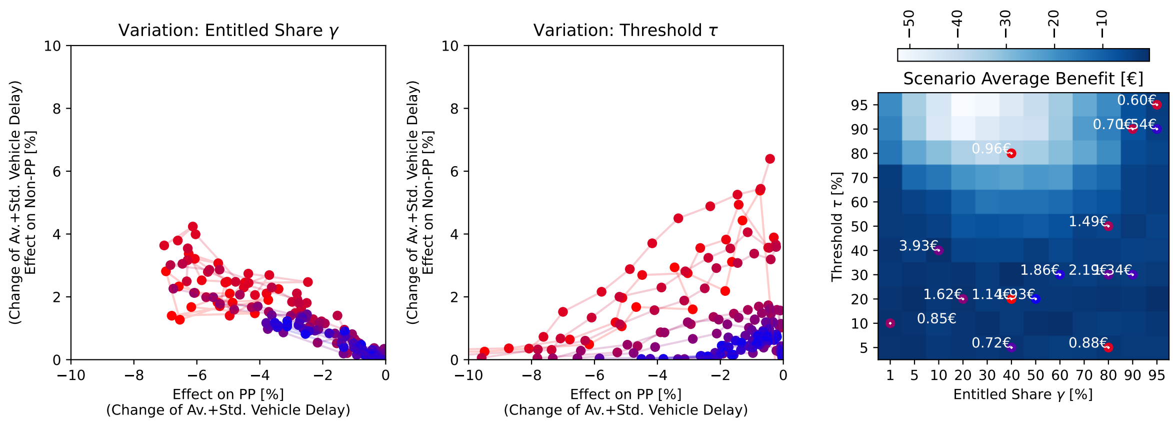
$$C = \frac{1}{|V|} \sum_{v \in V} D_v \times VOT_v \tag{4}$$

$$\mathcal{B} = C - C_{pp} \tag{5}$$

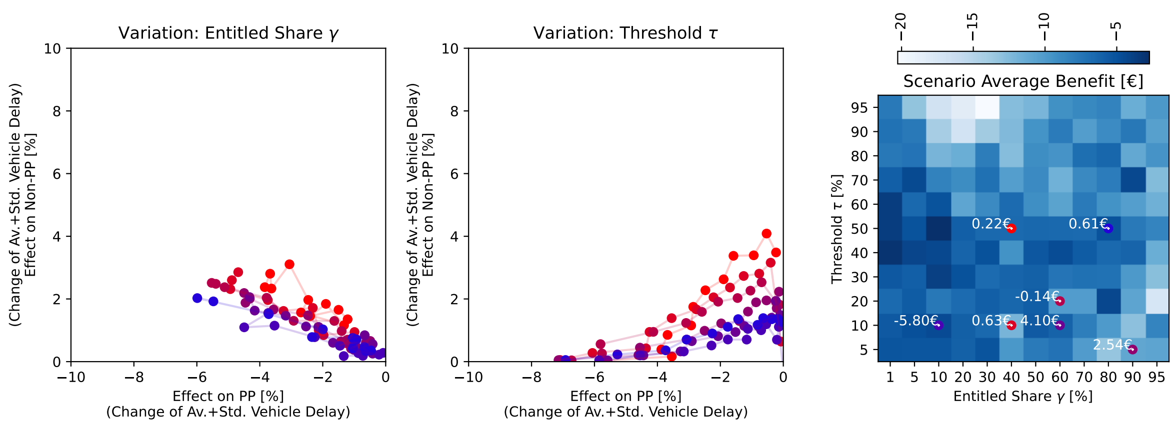
The costs (€) are derived from vehicles' delay D_v (seconds) and value of time VOT_v (€/seconds). For simplicity, we assume 2€/second for entitled and 1€/second for non-entitled vehicles.

Figure 4: Trade-Off (Entitled vs. Not-Entitled)

(A) Symmetric Scenarios



(B) Asymmetric Scenarios

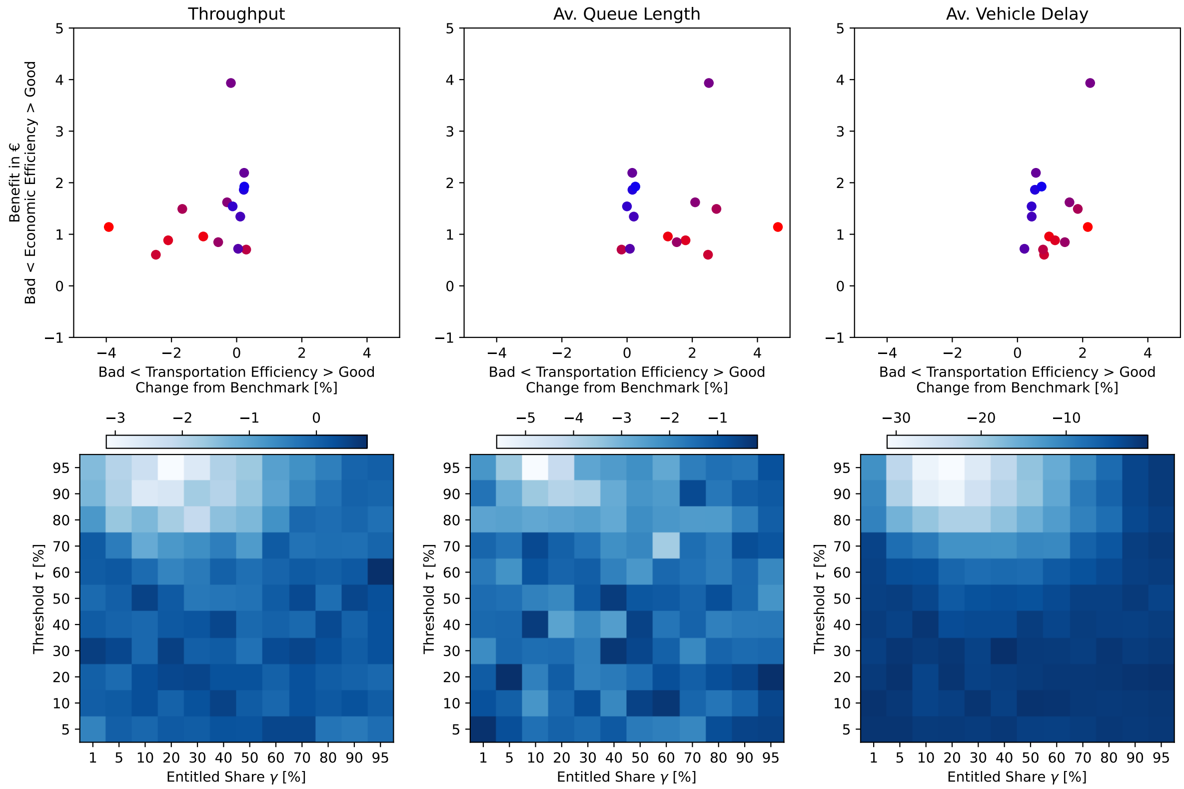


The relationship between transportation efficiency and economic efficiency is depicted in Fig. 5. Each point in the diagrams of the first row represents scenario-specific benefit maximizing parametrization. The heatmaps outline the effect of Priority Pass parameters on transportation efficiency; the darker the color the more desirable the influence.

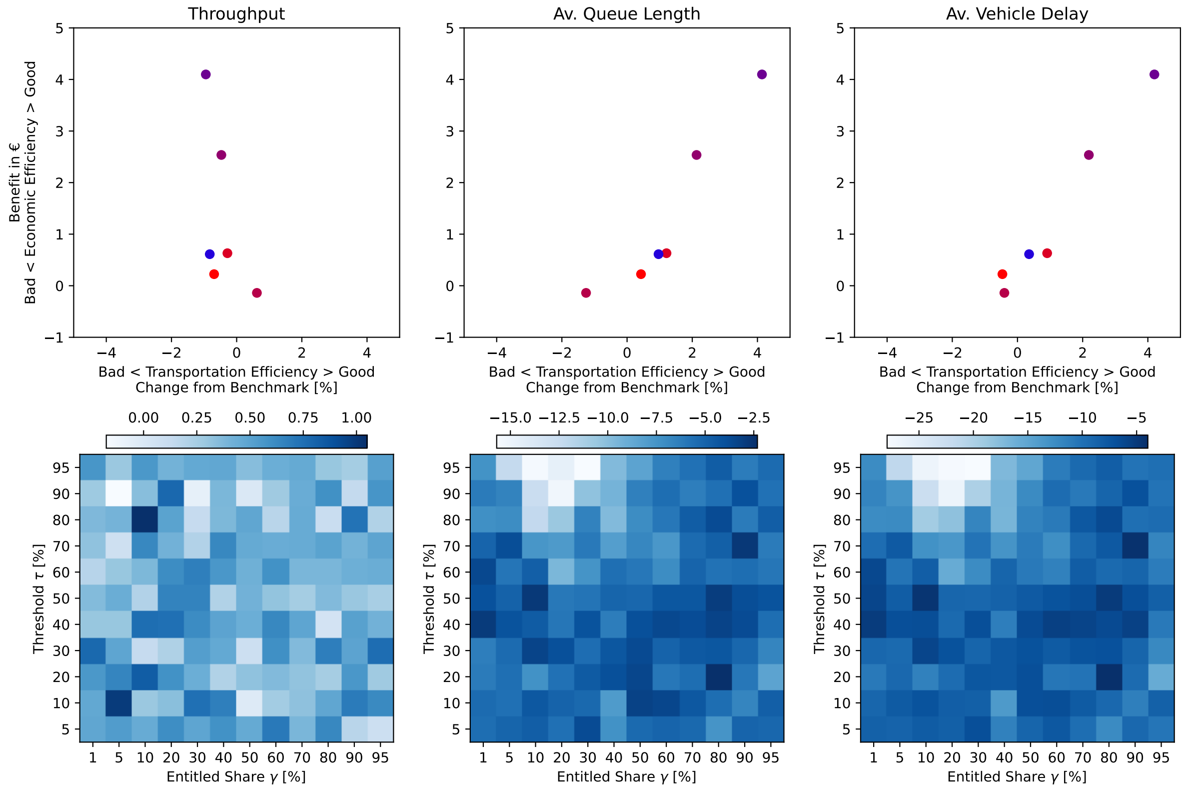
The areas of strongest disimprovement of transportation efficiency overlap with the areas of lowest economic efficiency. The results indicate, maximizing economic efficiency and transportation efficiency is not a conflict. In all cases, positive benefits (or negative benefits close to zero) could be achieved. As economic efficiency (measured in benefit $\mathcal{B}$) is linked with average vehicle delay, we see a positive goal relationship. The average queue length is also positively related, while the throughput is slightly negatively related. The economic efficiency tends to be greater at higher saturation.

Figure 5: Relationship of Transportation and Economic Efficiency

(A) Symmetric Scenarios



(B) Asymmetric Scenarios



4 Conclusions

This work proposes the feasible concept of a Priority Pass in signalized intersection management using auction controllers. The results emphasize, that the Priority Pass generates significant benefits for entitled vehicles, while it disadvantages non-entitled participants only a little, and effects on transportation efficiency are negligible. These insights hold robustly for different auction algorithms, levels of saturation and asymmetry.

In future works, we plan to study the interplay of multiple intersections in a case study based on a real city, elaborate on how such a Priority Pass could be optimally allocated to a vehicle population, and advance the modelling of the economic efficiency measure.

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