Priority Pass: Fair and Efficient Signalized Intersection Control

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1 INTRODUCTION

Road transportation systems are usually designed for optimizing transportation efficiency. A pure focus on efficiency overlooks, that passengers are not equal in their urgency; delays cause them different harm. Vehicle prioritization is a promising countermeasure to this equity issue. Existing strategies for prioritization can be grouped into three categories: dedicated lanes (e.g. public transport in Levinson *et al.* (2002)), legislative prioritization of blue light vehicles (e.g. ambulance in Nellore & Hancke (2016)), and economic instruments (e.g. high occupancy toll lanes in Dahlgren (2002)). There is no dedicated instrument that allows for prioritization at intersections in practice yet, even though intersections are a major source of delays in urban contexts.

In this work, we analyze, to which extent it is possible to expedite a certain share of vehicles at intersections, without causing arbitrary delays for the other vehicles or affecting transportation efficiency de trop. We propose the Priority Pass, a needs-based signalized intersection management. Entitled vehicles shall be prioritized at intersections, resulting in shorter delays. The Priority Pass is an intelligent transportation system, that builds upon auction-controllers, and existing, urban, vehicle-identifying infrastructure (Iliopoulou *et al.*, 2022). Experiments with varying number of prioritized vehicles, total traffic flows, and symmetry of demand, are conducted. The results demonstrate, that this concept generates significant benefits to the drivers, which do not come at the cost of transportation efficiency or arbitrary delays.

2 Methodology

The Priority Pass is a title, that is foreseen to be granted to a share γ of all vehicles for a specific time slot. The allocation of the entitlement to vehicles could happen through governmental assignment to blue light vehicles, or via markets, where drivers could trade-off travel time and money. Entitled vehicles could be considered in auction-based control (Iliopoulou *et al.*, 2022), where movement phase agents bid for the green phase. We consider sealed-bid, first-price, single-item auctions, where the bid $\widehat{b}_p$ of phase p equals the sum of two components: conventional bids

b_p (e.g. number of vehicles) 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 bidding schemes 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). In the first bidding scheme, the bid of a movement phase $b_{p,1}$ equals the number n_p of vehicles on the lanes that relate to that movement phase. In the second bidding scheme, each vehicle v_p of a movement phase is counted with a weight w_k depending on which lane-segment k it is located on; we consider following lane-segments (measured in meters before intersection): [<10, 10-20, 20-30, 30-40, 40-50, >50].

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

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

When choosing the Priority Pass hyper parameters γ and τ, one must consider two trade-offs: (i) the delay reductions of prioritized vehicles shall not come at the cost of arbitrary delays for not-entitled vehicles, and (ii) the total transportation efficiency shall not be affected by the introduction of the Priority Pass.

Vehicles that pass the road network will experience an average delay per travelled distance δ [sec/km]. This delay causes a cost c [€/km] to the drivers, depending on their urgency measured by their value of time y [€/h] (VOT): $c = \delta \times y$. The introduction of the Priority Pass will lead to two groups of vehicles, the entitled vehicles with an average delay of δ^{pp} and the not-entitled vehicles with an average delay of δ^{npp}. The benefit of the Priority Pass for an average vehicle c_r [€/km] can be quantified as the cost reductions when compared with the case of not-prioritizing, conventional signal control. The benefit of the Priority Pass for the total population C [€/h] can be quantified as the average vehicle's benefit c_r multiplied with the total flow of vehicles F [veh/h] and the average trip length l [km].

$$c_r = \gamma(\delta - \delta^{pp})y^{pp} + (1-\gamma)(\delta - \delta^{npp})y^{npp} \tag{4}$$

$$C = F \times c_r \times l \tag{5}$$

3 Results & Discussion

We compare the Priority Pass concept with a fixed-cycle-control, and conventional auction-controllers with movement-phase bidders ($\tau = 0$). Following efficiency measures are used for the comparison: throughput [veh/h], average vehicle delay [sec/km], and queue length [veh]. We conduct simulations with SUMO (Krajzewicz *et al.* (2012)); each experiment covers 60 minutes, and is repeated for 10 times. The road network consists of one intersection that is the crossing of two 500m long, single-direction lanes (north-south, and east-west). This 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, and asymmetric traffic flow scenarios. Throughout the study we assume conservative VOTs of 12 €/h for entitled and 6 €/h for not-entitled vehicles, when calculating monetary benefits.

The general relationship of delay change for entitled and not-entitled vehicles for different γ and τ is displayed in Figure 1. Intuitively, the more vehicles are entitled (larger γ), the less advantage there is for entitled vehicles, when compared to a situation without the Priority Pass. The more the auction-controller weights the Priority Pass vehicles (larger τ), the more delay reductions are observed for the entitled vehicles. With regards to the not-entitled vehicles, we find that delays increase for larger γ and τ. The average driver benefit c_r can help to trade-off delay changes of entitled and not-entitled vehicles, when finding optimal γ and τ.

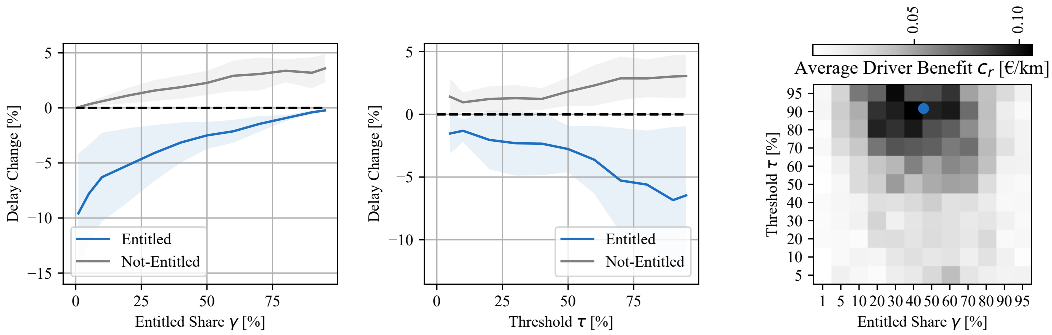

Figure 1 – *Mechanics of the Priority Pass (In-Flow 500 veh/h)*

An analysis of the Priority Pass for different traffic flows and scenarios is outlined in Figure 2. For increasing flows and higher levels of asymmetric traffic, the driver benefits increase. Delay reductions for entitled vehicles up to 8% can be achieved. Delays for not-entitled vehicles are not exceeding disproportionate levels, considering the relative VOT ratio. Entitlement shares γ of around 25% turn out to be optimal in this setup. The two different bidding strategies $b_{p,1}$ and $b_{p,2}$ deliver similar results. While $b_{p,1}$ is more robust, $b_{p,2}$ stands out for slightly higher average benefits, but more volatile results (higher standard deviations of delay distributions).

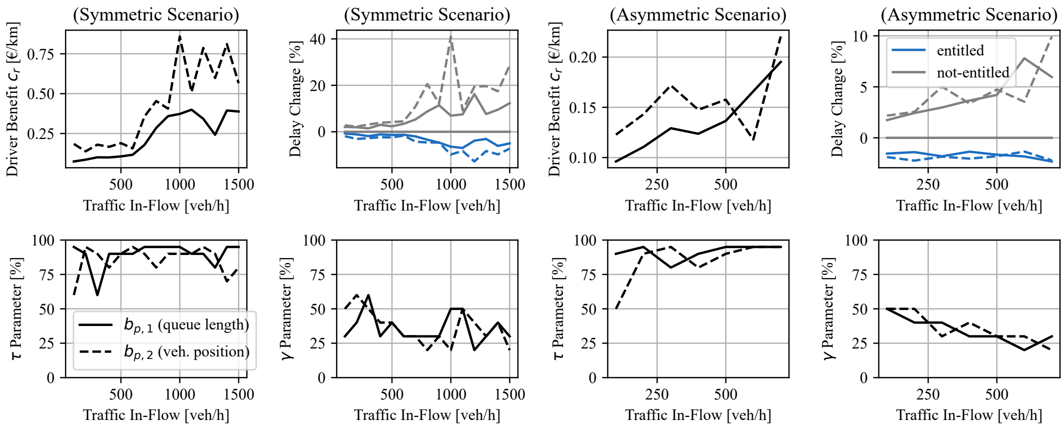

Figure 2 – *Trade-Off (Entitled vs. Not-Entitled)*

A transportation efficiency benchmark of the Priority Pass is shown in Figure 3. The Priority Pass controller is compared with fixed-cycle-control (baseline), and auction controllers. The results indicate that the effect of the Priority Pass on transportation efficiency is negligible, and that in some cases efficiency can even be improved, when compared to fixed-cycle control. The actuated control (auction-control) achieves better transportation efficiency when compared to the baseline, and can reduce average queue length & vehicle delay significantly. The Priority Pass control achieves around 5% less average queue length, 2.5% less throughput, and 5% more average vehicle delay. At the point of network saturation, when congestion starts, the actuated control and fixed-cycle control achieve similar levels of efficiency, and the Priority Pass control achieves its worst transportation efficiency.

The prioritization of drivers in need using the Priority Pass, generates a benefit for the society, as depicted in Figure 4. From a decentralized (market) allocation point of view, where drivers can buy the Priority Pass, significant revenues of around 250€/h could be generated during peak times, using conservative assumptions on driver's willingness to pay & VOT for entitled and not-entitled vehicles. From a centralized (governmental) allocation point of view, where ambulances, fire brigade, or police vehicles get prioritized, a much stronger difference in the VOT can be assumed, with even higher societal benefits.

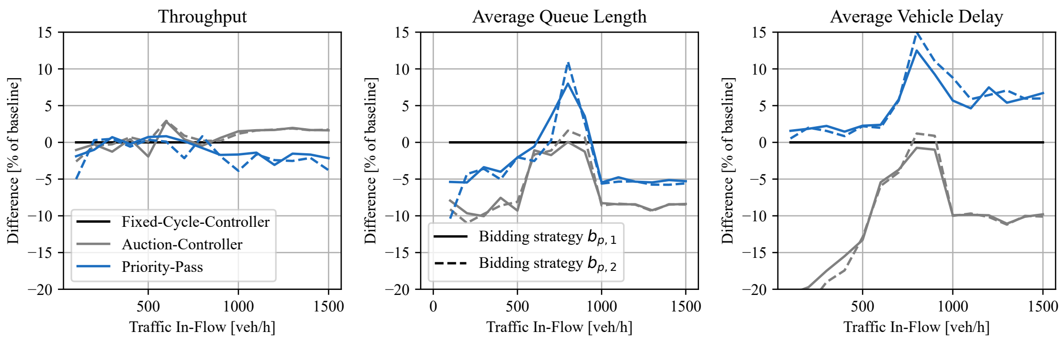

Figure 3 – *Priority Pass and Transportation Efficiency*

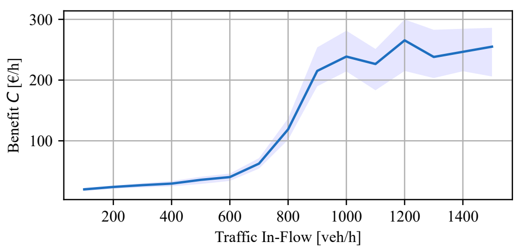

Figure 4 – *Societal Benefit of Priority Pass*

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