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Dynamic Pricing for Toll Lanes – a Case Study

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Abstract: This paper reports about the development, analysis, simulation, and real-life measurements of the dynamic toll fee control algorithm for the recently opened Fast Lane, i.e. the additional parallel HOT lane on the part of the Jerusalem - Tel Aviv Highway 1 with three free lanes that runs westwards between the Ben Gurion Airport and Tel Aviv. It was found that cascaded feedback control is suitable, where the inner loop determines the toll fee increment with the inflow to the HOT lane as feedback signal, while the outer loop determines the inflow reference based on the average speed on the HOT lane as the feedback signal, and the government mandated lower average speed as its reference. Measured morning rush hour data for the toll lane under manual and automatic control are presented.

Keywords: Traffic control, Cascade control, HOT lane, Dynamic pricing, Toll fee determination.

1. INTRODUCTION

High Occupancy/Toll (HOT) lanes are an attractive alternative to High Occupancy Vehicle (HOV) lanes when the High Occupancy Vehicle flow does not fully utilize the lane capacity. In order to avoid congestion in the HOT lane that will also hurt the prioritized HOV flow, dynamic pricing has been suggested and implemented at various locations around the world. A review on traffic congestion pricing methodologies and technologies is found in (de Palma & Lindsey 2011) with a list of 140 references. An overview of current best practice, and economic and transport benefits of congestion pricing is found in e.g. (Murray 2012).

Various real-time congestion pricing schemes for toll lanes have been suggested, based on various assumptions about the statistical distribution of the drivers' Value of Time (VoT). In (Laval et al. 2015) it was found that minimum total system delay can be achieved with many different pricing strategies. Maximum revenue is achieved by keeping the toll lane at capacity. An algorithm to minimize the total travel time is proposed in (Hong, Lee & Lee 2015). In a numerical study in (Cheng and Ishak 2015) using VisSim and based on data from I-95 in Florida, a dynamic toll pricing strategy based on feedback control rules compares favourably with the current performance. Based on real data from I-680 in San Fransisco, in the simulation study (Jang, Chung & Yeo 2014) the HOT lane toll is determined in a feedforward fashion from measured total flow and estimated VoT in order to keep the HOT flow below capacity. In (Lou, Yin, and Laval 2011) the dynamic toll to maximize the throughput of the freeway is based on the recursive learning the motorists' VoT.

While the above works are all analytical and based on simulations, (Hourdos et al. 2015) studies the Minnesota MnPASS HOT lane experimentally. At present the toll is a function of HOT lane congestion given as a look-up table, and it is found that it is prone to break-downs since it does not react fast enough. In the experiments the authors changed the toll at will, and observed that when the price increased, the HOT lane demand increased! This is explained by the fact that the drivers do not get any comparative congestion information at the entrances to the HOT lane, and hence believe that the toll reflects the congestion on the general lanes. A simulation tool using AimSun was developed with VoT estimated from data.

In contrast to most previous studies, this contribution presents the development of a toll determination algorithm based on classical feedback control (Åström and Murray 2008) that was implemented on a HOT lane with measurements and comparison with manual control. The paper is organized as follows: In section 2 the controlled object, namely the 11.4 km long HOT lane/Highway 1 stretch from Ben Gurion Airport to the Kibbutz Galuyot entrance of Tel Aviv, and the government imposed level of service specification are described. Section 3 describes a simple dynamic model of the HOT lane/Highway 1 system based on step response experiments with a VisSim model that was developed prior to the opening of the HOT lane. The feedback control algorithm is presented and analysed in the frequency and time domains in section 4. Section 5 shows real-life measurements with manual control, and two recordings of automatic control with our algorithm. The conclusions follow in section 6.

2. PROBLEM DEFINITION

The Fast Lane (FL) is the 11.4 km long HOT lane parallel to Highway 1 (HW1) westwards from Ben Gurion Airport (BG) to the Kibbutz Galuyot interchange at the entrance to Tel Aviv, see Fig. 1. HW1 has the Shapirim Interchange 5.5 km east of BG, and the Gannot Interchange 1.7 km further west. The FL has one exit/entry point midway, after 5 km, where also the Park-and-Ride facility is located. The eastern FL section from BG to the Park-and-Ride is toll free, lately also

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for those who do not use the Park-and-Ride due to the fact that most often the parking lot fills up early in the morning. However, in general, the congestion on HW1 starts only at the Gannot or Shapirim interchange, so there is little incentive for the toll-shy driver to use the FL to drive to the Park-and-Ride, make a little detour inside it, and then continue on HW1.

The government mandated Level-of-Service on the FL that the toll fee determination control algorithm has to satisfy is that each individual driver's average speed on each one of the two FL sections be at least 70 km/h, i.e. the FL should be traversed in 10 minutes. If the average speeds are not achieved, the driver will not have to pay the toll. The FL is equipped with number plate identification systems, and subscribers pay the toll via automatic bank transfer, while others pay at the Park-and-Ride plaza. At inception the toll ranged between 5 and 70 ILS (1 USD = 3.5 ILS), today the range is [7, 97] ILS. If the toll determination algorithm demands a higher fee, then non-HOV vehicles are forbidden to enter. It was originally estimated that up to 400 HOVs/hr would use the FL whose capacity is up to 1600 veh/hr.

At the entries to the FL two items are displayed: the toll, and the congestion status on HW1 in form of the location where the congestions starts, i.e. from Ben Gurion, from Shapirim, from Gannot, or no congestion. Since the experienced driver knows how to translate this information into approximate travel times, and it is known that the FL is controlled in such a way that its traversal takes 10 minutes, the driver can make an intelligent estimate if the time saving is worth the toll. Moreover, Waze and other widely used real-time navigation apps make quite accurate predictions about the travel time of the two alternatives. The error is in general within ± 2 min.

3. A SIMPLE DYNAMIC PLANT MODEL

Before inception a VisSim model was built for the FL/HW1 system. By simulated step response experiments, a simple non-linear difference equation model was constructed and tuned by the least squares method to serve as a model for control design for the case the FL operated normally, and HW1 was potentially congested:

$$Q_{hw}(t) = (1 - p(t))Q(t) \quad (1)$$

$$Q_{FL}(t) = p(t)Q(t) \quad (2)$$

$$v_1(t) = -0.0058 Q_{FL}(t-4) + 94.952 \quad (3)$$

$$v_2(t) = -0.0055 Q_{FL}(t-10) + 92.3824 \quad (4)$$

$$T_{FL}(t) = 0.0298 Q_{FL}(t-10) + 415.4068 \quad (5)$$

$$q(t) = \max(0, q(t-1)) + 0.0139 Q_{hw}(t) - 45.4386 \quad (6)$$

$$T_{hw}(t) = q(t-4) + 450 \quad (7)$$

Here, t [min] is time; $Q(t)$ [veh/hr] is the upstream traffic flow from the east; $p(t)$ is the proportion of the vehicles choosing the FL; $Q_{hw}(t)$ [veh/hr] is the flow entering HW1; $Q_{FL}(t)$ [veh/hr] is the flow entering the FL; $v_1(t)$ [km/h] is the mean speed on the eastern FL Section 1; $v_2(t)$ [km/h] is the mean speed on the western FL Section 2; $T_{FL}(t)$ [sec] is the time to traverse the FL; $q(t)$ [sec] is the delay due to congestion on HW1; and $T_{hw}(t)$ [sec] is the time to traverse HW1. It is simplistically assumed that the in- and outflow at the Park-and-Ride plaza and the HW1 intersections equal out.

Several interesting observations can be made from the above equations. The empty-FL speeds are 94 and 92 [km/h], respectively, and the speed decreases with increasing flow. The empty-FL traversal time is 415 [sec] and increasing with increasing flow. Equation (6) which contains a conditional integrator, gives that congestion on HW1 builds up when its flow exceeds 45.4386/0.0139 = 3267 [veh/hr]. The non-congested HW1 traversal time is 450 [sec]. Note the considerable transport delay terms in (3)-(7).

For design and analysis purposes, a quite unrealistic nominal Value-of-Time function (VoT) [ILS/hr] was assumed:

$$x(t) = \frac{F(t)}{T_{hw}(t) - T_{FLnom}} \cdot 3600 \quad (8)$$

$$P(x) \in \mathcal{N}(35, 17.5) \quad (9)$$

$$p(t) = \int_{x(t)}^{\infty} P(s)\,ds \quad (10)$$

Here, $F(t)$ [ILS] is the current toll; and T_{FLnom} [sec] is the nominal time to traverse the FL, set to 450 [sec]. $T_{hw}(t)$ and T_{FLnom} are assumed known to the driver. Hence, $x(t)$ [ILS/hr] is the critical VoT at time *t*. $P(x) \in [0,1]$ is the driver probability distribution function with respect to VoT, assumed to be Gaussian, with mean = 35 [ILS] and standard deviation = 17.5 [ILS]. $p(t) \in [0,1]$ is then the proportion of the vehicles choosing the FL. Note that in the verification simulations it was assumed that the parameters of (8), (9) were different from the nominal parameters that the controller design was based upon. A more realistic VoT function is found in e.g. (Jang, Chung & Yeo 2014).

To get a feeling for the plant, (1)-(10) were linearized at the operating point $T_{hw}(t) = 4\,T_{FLnom}$, $Q(t) = 5400$ [veh/hr] with

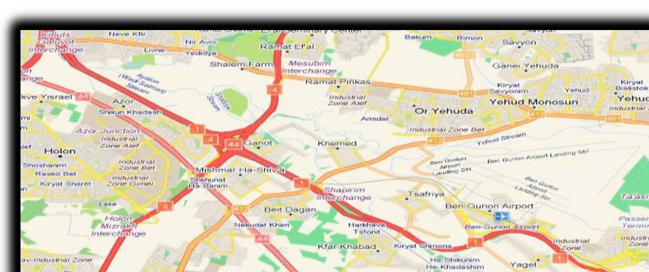

Fig. 1. Overview map of the route of HW1 and the FL.