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Doubling throughput in urban roads by platooning ★

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Abstract: Intersections are the bottlenecks of the urban road system because an intersection's capacity is only a fraction of the vehicle flows that the roads connecting to the intersection can carry. The saturation flow rate, and hence the capacity, can be doubled if vehicles can cross intersections in platoons rather than one by one as they do today. Platoon formation is enabled by connected vehicle technology. Doubling the saturation flow rate has dramatic mobility benefits: the throughput of the road system can be doubled without changing the signal control, or vehicle delay can be reduced by reducing the cycle time. These predictions draw on an analysis of a queuing model of a signalized network with fixed time control and they are validated in a simulation of a small urban network with 16 intersections and 73 links.

Keywords: Connected vehicles, saturation flows, platooning, adaptive control, reducing delay

1 Introduction

Connected vehicle technology (CVT) is founded on the capability of vehicles to communicate in a mobile environment using dedicated short-range communications (DSRC). CVT has aroused interest in the academic community and in automobile and IT companies.

Academic research has shown that DSRC can support mobile networks with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication (Bezzina and Sayer (2015)). There also is research on coordinated vehicle control using V2V communication to enable maneuvers such as merging, cooperative adaptive cruise control (CACC) (Ploeg et al. (2011); Kianfar et al. (2012); Milanes et al. (2014)) and passage through an intersection without signals (Au et al. (2015)). The NHTSA report (Harding et al. (2014)) describes the enhanced safety that V2V communications potentially offers in pre-crash scenarios. Commercial effort in CVT seeks to stimulate and meet consumer demand to connect cars to the internet. None of this research is concerned with enhancing mobility on urban roads.

By contrast, this paper explores the use of CVT to dramatically increase the capacity of urban roads based on the simple idea that if CVT can enable organizing vehicles into platoons, the capacity of an intersection can be increased by a factor of two to three. §2 sketches a scenario showing how platooning increases an intersection's capacity by increasing its saturation flow rate. It points to research that demonstrates platooning using CACC implemented on ACC-equipped commercial vehicles augmented with V2V communication. §3 analyzes a queuing network model to show that an increase in the saturation flow rate by a factor γ can support an increase in demand in the same proportion, with no change in the signal control. Alternatively, the gain γ can be used to reduce the intersection delay by reducing the cycle time, while maintaining the red clearance times. The simulation exercise in §4 confirms these predictions. §5 presents the challenges of the real world implementation of platooning. §6 summarizes the main conclusions of this study.

2 Intersection capacity

The Highway Capacity Manual (HCM) defines an intersection's capacity as

$$\text{Capacity} = \sum_i s_i \frac{g_i}{T}. \tag{1}$$

Here T is the cycle time and, for lane group i, s_i is the saturation flow rate and g_i/T is the effective green ratio. HCM takes $s_i = N \times s_0 \times f$: N is the number of lanes in the group, s_0 is the base rate in vehicles per hour (vph), and f is an 'adjustment factor' that depends on the road geometry and traffic characteristics. HCM suggests $s_0 = 1,900$ vph. Since $s_i \times (g_i/T)$ is the rate at which vehicles in queue in group i can potentially be served by the intersection, we also call it the *service rate* in a queuing model of this lane group.

Consider an intersection with four approaches, each with one through lane and one left-turn lane. There are thus eight movements in all, two movements per approach. If each lane supports

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Table 1. A trace of vehicles entering an intersection from one through lane during one green phase

Number	Time after phase starts	Time before phase ends	Occupancy sec	Speed mph
1	3.47	47.28	63.88	17.53
2	5.85	44.91	0.44	28.33
3	8.35	42.41	0.81	33.43
4	11.22	39.53	0.81	24.52
5	14.16	36.59	0.56	33.53
6	25.53	25.22	0.31	52.75
7	33.41	17.34	0.44	52.75
8	34.1	16.66	0.38	52.51
9	36.41	14.34	0.56	40.93
10	37.91	12.84	0.56	52.75
11	39.1	11.65	0.5	40.93
12	45.03	5.72	0.12	73.72

a flow of 1,900 vph, the four approaches can carry a total of $1,900 \times 8 = 15,200$ vph. However, only two movements can safely be permitted at the same time, so the effective green ratio for each movement is at most 0.25, and from equation (1) the capacity of the intersection is only 3,800 vph. Thus the intersection is the principal bottleneck in urban roads: its capacity is a fraction (here 1/4) of the capacity of the roads connecting to it.

Table 1 displays the measured trace of detector events from 12 vehicles that enter a through lane in an intersection during one cycle with a green phase duration of 50 sec for the through movement. The second and third columns give the times (in sec) after the start of green and before the end of green when each vehicle enters the intersection, the fourth column gives the duration of time the vehicle 'occupied' the detector zone, and the fifth column lists an estimate of its speed. The detectors have a sampling frequency of 16 Hz, so the speeds are quantized: speeds above 60 mph have a quantization error of about 15 mph, speeds below 30 mph have an error under 5 mph. The average speed of the 12 vehicles is 42 mph. The speed limit at this intersection is 50 mph. The first vehicle entering the intersection has a delay or reaction time of 3.47 sec. The first 5 vehicles enter within 14.16 sec, so the empirical saturation flow rate of this movement is 14.16/5 = 2.83 sec per veh or 3600/2.83 = 1272 veh/hour. Vehicles 5, 6, $\cdots$ travel at much higher speed. Note that the time headway (time from the tip of one vehicle to the tip of the next one behind it) between vehicles 7 and 8 is only 0.7 sec.

Suppose these 12 vehicles were to move together as a platoon at a speed of 45 mph (66 feet/sec) and a uniformly small time headway of (say) 0.75 sec. This would give a saturation flow rate of $3600/0.75 = 4800$ vph, which is 3.8 times the observed rate of 1272 vph and 2.5 times HCM's theoretical rate of 1900 vph. A quick estimate for a platoon crossing an intersection at 30 mph (44 feet/sec) with space headway of 40 feet (time headway of 40/44 sec) is a platoon saturation flow rate of (44/40) $\times$ 3600 = 3960 vph, which is twice HCM's 1900 vph and up to three times the rates observed in today's intersections.

What does it take to organize a platoon? If the 12 vehicles queued at or approaching the intersection were 'connected' that is, if they were to communicate with each other as well as with the signal controller, their longitudinal motion could be coordinated in such a way that they would move together as a platoon and thereby increase the saturation flow rate by a factor of two or three. Milanes et al. (2014) report an experiment of a 4-vehicle platoon, capable of cut-in, cut-out and other maneuvers, using CACC technology. The vehicles had factory-equipped ACC and their capability was enhanced by a DSRC radio that permitted V2V communication needed to enable CACC. The vehicles in the platoon experiment had a time gap of 0.6 sec (time headway of 0.8 sec) traveling at 55 mph. Ploeg et al. (2011) report an experiment of a 6-vehicle CACC platoon, with a 0.5s headway. The ACC equipped vehicles were augmented with V2V communications using a IEEE 802.11p WiFi radio in ad-hoc mode.

It is important to distinguish our proposal to use CACC to increase an intersection's capacity from proposals to use CACC to increase a highway's capacity by decreasing headway. Increasing the throughput of urban roads will *not* increase the throughput of the urban network which is limited by intersection capacity.

3 Three predictions

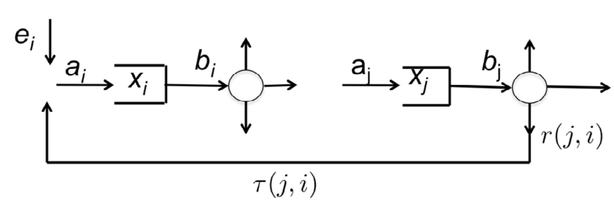

Fig. 1. Fluid network model. Source: Muralidharan et al. (2015).

Imagine that all saturation flow rates in an urban road network of signalized intersections are increased by the same factor of 2 to 3 using platoons. We explore the implications of such a productivity increase, assuming that all signals use a fixed-time control with the same cycle time T. We use a fluid model of a network of signalized intersections for our exploration. The model is studied by Muralidharan et al. (2015) and illustrated in Figure 1.

There are J queues in the network, each corresponding to one turn movement. A specified fraction $r(j,i)$ of the vehicles departing from queue j is routed to queue i. Queue i also has exogenous arrivals with rate $e_i(t)$. The exogenously specified service rate of queue i, $c_i(t)$, is periodic with period T: $c_i(t)$ is the saturation flow rate when the light is green and $c_i(t) = 0$, when it is red. $x_i(t)$ is the queue length of i and $b_i(t)$ is its departure rate at time t. $a_i(t)$ denotes the total arrival rate into queue i at time t. The travel time from queue j to queue i on link (j,i) is $\tau(j,i)$ as in the figure. The network dynamics are as follows.

$$\dot{x}_i(t) = a_i(t) - b_i(t), \tag{2}$$

$$a_i(t) = e_i(t) + \sum_{j=1}^{J} b_j(t - \tau(j,i)) r(j,i), \tag{3}$$

$$b_i(t) = \begin{cases} c_i(t), & \text{if } x_i(t) > 0, \\ \in [0, c_i(t)], & \text{if } x_i(t) = 0, \\ 0, & \text{if } x_i(t) < 0. \end{cases} \tag{4}$$

(2) says that the queue length is the cumulative difference between arrivals and departures; (3) says that the arrivals into queue i is the sum of exogenous arrivals and those routed to i from other queue; (4) says that queue i is served at its service rate $c_i(t)$. This is a nonlinear delay-differential inclusion. Although the inclusion is not Lipschitz, Muralidharan et al. (2015) show that the system has a unique solution for $x_i(0) \geq 0$. The