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Determining Progression Adjustment Factor and Upstream Filtering Adjustment Factor at Signalized Intersections

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ABSTRACT

In the Highway Capacity Manual there are two factors accounting for the platooning in vehicle arrivals and filtering effect caused by the upstream signals: a) the progression adjustment factor and b) the upstream filtering adjustment factor. The progression adjustment factor is only descripted by the arrival types. In a planning scenario, the planner is not able to determine the progression adjustment factor according to the proposed traffic demand and signal timing plan. The upstream filtering adjustment factor is defined as a function only of the volume-to-capacity ratio of the upstream signal. This is not sufficient.

For overcoming both problems mentioned above, some useful derivations which can be used as a default solution given the traffic demand and signal setting in a planning scenario are presented. The solution is based on a generalized model which is compatible to the existing procedure in the HCM.

Keywords: Traffic Signal, Progression, Progression adjustment factor, Upstream Filtering Adjustment Factor

INTRODUCTION

In the Highway Capacity Manual (HCM) (TRB, 2000, 2010) there are two factors accounting for the platooning in vehicle arrivals and filtering effect caused by the upstream signals: a) progression adjustment factor and b) upstream filtering adjustment factor. The progression adjustment factor is used to describe the quality of signal progression for the corresponding movement group. It is computed as the demand flow rate during the green time divided by the average demand flow rate. By default, the progression adjustment factor can be obtained by using the arrival type designation. The upstream filtering adjustment factor accounts for the effect of an upstream signal on vehicle arrivals to the subject movement group. Specifically, this factor reflects the way that an upstream signal changes the variance in the number of arrivals per cycle. The variance decreases with increasing bunched vehicles, which can reduce cycle failure frequency and resulting delay.

In the HCM, the progression adjustment factor is only descripted by arrival types. The arrival types are defined by the so-called platoon ratio. However, no equations or diagrams for estimating arrival types and thus for the platoon ratio are given. In a planning scenario, the planner is not able to determine the platoon ratio according to the proposed traffic demand and signal timing plan.

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For determining the upstream filtering adjustment factor, the HCM provides a regression formula which is only a function of the volume-to-capacity ratio of the upstream signal. This is not sufficient. The upstream filtering adjustment factor depends not only on the upstream volume-to-capacity ratio but also on the proportion of the upstream green time and on the in-turning flow rate from the side roads.

This paper presents some useful derivations both for the upstream filtering adjustment factor and for the progression adjustment factor. The results can be used as a default solution given the traffic demand and signal setting in a planning scenario. The solution is based on a generalized model which is compatible to the existing procedure in the HCM.

DELAY ESTIMATION IN HCM

In the HCM (TRB 2010, 2000), the control delay d at signalized intersections is divided in three parts, a) uniform delay d_1 assuming uniform arrivals, b) incremental delay d_2 to account for effect of random and oversaturation, and c) initial queue delay d_3 accounting for initial queue at start of analysis period. For a single interval analysis we are interested here only in the uniform delay d_1 and the incremental delay d_2.

Both in HCM2010 and HCM2000 the incremental delay d_2 is calculated by the fowling equation:

$$d_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right] \tag{1}$$

with

$$X = v/c$$

where

d_2 = incremental delay accounting for effect of random and oversaturation, s
X = the volume-to-capacity ratio, -
c = capacity, veh/h
T = duration of the analysis period, h
I = upstream filtering adjustment factor, -
k = incremental delay factor varying in value from 0.04 to 0.50, -
For fix-timed signals k = 0.5 for M/D/1 queuing system as an approximation of queuing system at signalized intersections.

The upstream filtering adjustment factor I accounts for the effect of an upstream signal on vehicle arrivals to the subject movement group. Specifical1y, this factor reflects the way an upstream signal changes the variance in the number of arrivals per cycle. The variance decreases with increasing volume-to-capacity ratio, which can reduce cycle failure frequency and resulting delay.

According to HCM methodology, the uniform delay d_1 can be calculated by the equation

$$d_1 = \frac{0.5C(1-g/C)}{1-[\min(1,X)g/C]}PF \tag{2}$$

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with

$$PF = \frac{1-P}{1-g/C} \tag{3}$$

where

d_1	=	uniform delay d_1, s
PF	=	progression adjustment factor, -
P	=	proportion of vehicles arriving on green volume-to-capacity ratio, -
g/C	=	proportion of green time available, -
g	=	green time, s
C	=	cycle time, s

The value of P may be measured in the field or estimated from the arrival type. If field measurements are carried out, P should be determined as the proportion of vehicles in the cycle that arrive at the stop line or join the queue (stationary or moving) while the green phase is displayed.

In the following sections, new approaches both for the upstream filtering adjustment factor I and for the progression adjustment factor PF are developed.

NEW APPROACHES FOR THE UPSTREAM FILTERING ADJUSTMENT FACTOR AND THE PROGRESSION ADJUSTMENT FACTOR

Determining Upstream Filter Adjustment Factor

The upstream filtering adjustment factor reflects the way that an upstream signal changes the variance in the number of arrivals per cycle. The following equation is used to compute upstream filtering adjustment factor I for non‐isolated intersections (HCM 2010, Equation 18 3).

$$I = 1.0 - 0.91 X_u^{2.68} \geq 0.090 \tag{4}$$

where

I	=	upstream filtering adjustment factor, -
X_u	=	volume-to-capacity ratio of upstream through movement (for default condition), -

The upstream filtering adjustment factor I descript actually the ratio between the delay with random arrivals and the delay with bunched arrivals under the condition of progression. If the proportion of the bunched vehicles, i.e. vehicles in platoon, is known, this factor is also known. According to the derivation from Marshal (1974) and from an early work of the Author (Wu, 1990), the total queue length L (including customer in service) and the total delay d of a G/G/1 system can be approximated by the following equations:

$$L = X + N = X + k_{st}\frac{X^2}{1-X} \quad \text{and} \quad d = \frac{L}{q} = b + k_{st}\frac{bX}{1-X} \tag{5}$$

with

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L = total queue length including customer in service, -
X = degree of saturation, -
N = queue length in queue, number of vehicle, -
= $q \cdot b$-
k_{st} = randomness factor of a queuing system, -

$$\cong \frac{1+b^2\sigma_b{}^2}{\frac{1}{b^2\sigma_b{}^2}+b^2\sigma_b{}^2}\left[\frac{\sigma_a{}^2+\sigma_b{}^2}{2}\right]\cdot\frac{1}{b^2}$$

q = flow rate, veh/s
b = service time, s
$\sigma_a{}^2$ = variance of inter-arrival time, s^2
$\sigma_b{}^2$ = variance of service time, s^2

For the queuing system at signalized intersections one can assume σ_b=0. Thus,

$$k_{st} \cong \frac{q^2}{2}\sigma_a{}^2$$

Only vehicles in free (non-bunched) condition contribute to the variance of inter-arrival time, $\sigma_a{}^2$. Thus, the ratio between the randomness factor of a queuing system with random arrivals and the randomness factor of a queuing system with bunched arrivals, I^*, can be expressed as

$$I^* = \frac{k_{st,bunch}}{k_{st,free}} = \frac{q_{bunch}{}^2\frac{\sigma_a{}^2}{2}}{q_{free}{}^2\frac{\sigma_a{}^2}{2}} = \frac{q_{bunch}{}^2\frac{\sigma_a{}^2}{2}}{q_{free}{}^2\frac{\sigma_a{}^2}{2}} = \frac{q_{bunch}{}^2}{q_{free}{}^2} = (1-\frac{q_{pl}}{q})^2 = (1-P_{pl})^2 \quad (6)$$

where

I^* = ratio between the randomness factor of a queuing system with random arrivals and the randomness factor of a queuing system with bunched arrivals, -
P_{pl} = proportion of the bunched (in platoon) vehicles, -

The proportion of the free vehicles is then

$$P_{free} = 1-P_{pl} \quad (7)$$

The ratio between the total delay or queue length with random arrivals and the total delay in queue or queue length with bunched arrivals, i.e. the upstream filtering adjustment factor, I, is then

$$I = \frac{L_{bunch}}{L_{free}} = \frac{d_{bunch}}{d_{free}} = \frac{I^* N_{free}+X_d}{N_{free}+X_d} = \frac{(1-P_{u,pl})^2 N_{free}+X_d}{N_{free}+X_d} \quad (8)$$

where

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$P_{u,pl}$ = proportion of the bunched (in platoon) vehicles in the upstream, -
X_d = degree of saturation in the downstream, -

For the general case with *n* upstream streams we have (see Figure 1)

$$P_{u,pl} = \frac{\sum_{i=1}^{n} \left(P_{u,pl,i} \cdot q_{u,i} \right)}{\sum_{i=1}^{n} q_{u,i}} \qquad (9)$$

and again

$$P_{u,free} = 1 - P_{u,pl} \qquad (10)$$

Figure 1. Possible upstream streams

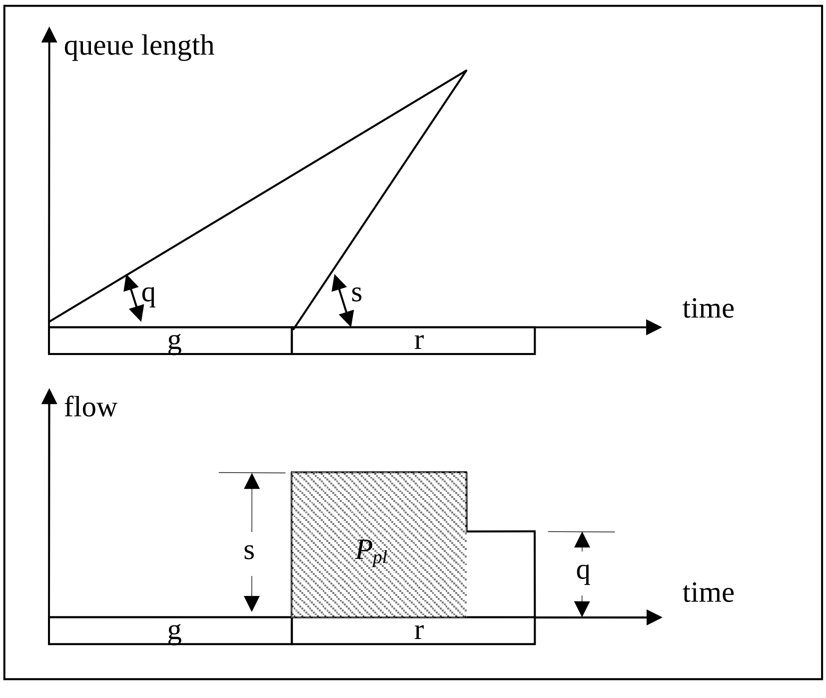

Figure 2. Proportion of platoon P_{pl}

The proportion of the bunched (in platoon) vehicles can be calculated as the proportion of the amount of discharging vehicles and the total amount of vehicles. According to the discharge flow patterns within a signal cycle length, the proportion of the bunched vehicles in the upstream at an isolated upstream intersection is (see

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Figure 2)

$$P_{u,pl,i} = \frac{1-f_{u,i}}{1-f_{u,i}X_{u,i}} \tag{11}$$

The parameter $f_{u,i}$ =g/C is the ratio of green time in the i-th upstream. Thus, for n upstream streams we have

$$P_{u,pl} = \frac{\sum_{i=1}^{n}\left(P_{u,pl,i}\cdot q_{u,i}\right)}{\sum_{i=1}^{n} q_{u,i}} = \frac{\sum_{i=1}^{n}\frac{1-f_{u,i}}{1-f_{u,i}X_{u,i}}q_{u,i}}{\sum_{i=1}^{n} q_{u,i}} \tag{12}$$

For n=1, i.e., there is only one upstream with considering bunched vehicles, is

$$P_{u,pl} = \frac{1-f_u}{1-f_uX_u} \text{ and } P_{u,free} = 1-\frac{1-f_u}{1-f_uX_u} = \frac{f(1-X_u)}{1-f_uX_u} \tag{13}$$

(in case of no right-turners using through lanes)

In case of n=1 and all in-turning streams from the side roads are considered consisting of only free vehicles is

$$P_{u,free} = \frac{M_{free}}{M_u+M_{in-turn}} = \frac{M_u\frac{f_u(1-X_u)}{1-X_uf_u}+M_{in-turn}}{M_u+M_{in-turn}} = \frac{q_u\frac{f_u(1-X_u)}{1-X_uf_u}+q_{in-turn}}{q_u+q_{in-turn}}$$
$$= \frac{\frac{f_u(1-X_u)}{1-X_uf_u}+\frac{q_{in-turn}}{q_u}}{1+\frac{q_{in-turn}}{q_u}} = \frac{\frac{f_u(1-X_u)}{1-X_uf_u}+Q_{in-turn}}{1+Q_{in-turn}} = I^* \tag{14}$$

$$P_{u,pl} = 1-P_{u,free} = 1-\frac{\frac{f_u(1-X_u)}{1-X_uf_u}+Q_{in-turn}}{1+Q_{in-turn}} = \frac{1-\frac{f_u(1-X_u)}{1-X_uf_u}}{1+Q_{in-turn}} = \frac{\frac{1-f_u}{1-X_uf_u}}{1+Q_{in-turn}} \tag{15}$$

with $Q_{in-turn} = \frac{q_{in-turn}}{q_u}$ = ratio of upstream through and total in-turning volume, -

Thus, for this very common case is

$$I = \frac{I^*N_{free}+X_d}{N_{free}+X_d} = \frac{\left(1-\frac{1-f_u}{(1-X_uf_u)(1+Q_{in-turn})}\right)^2 N_{free}+X_d}{N_{free}+X_d} \tag{16}$$

with

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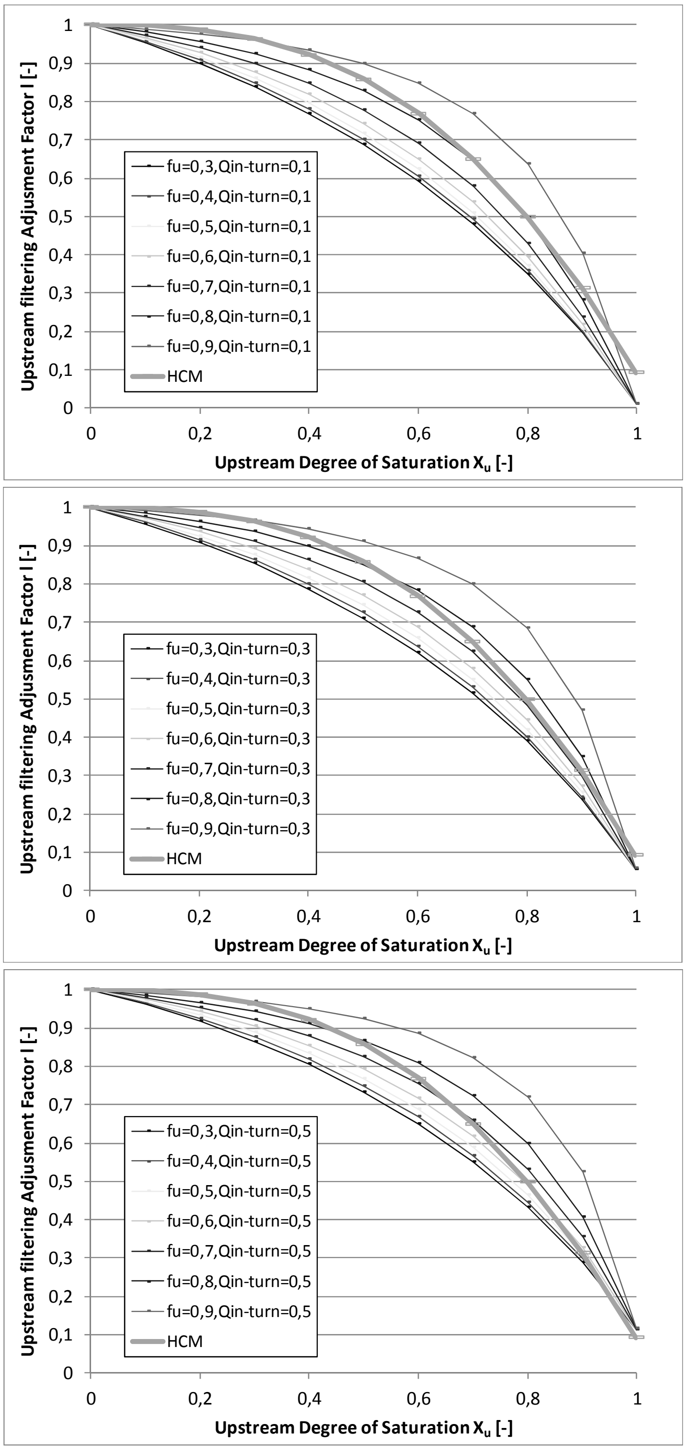
$$N_{free} = \frac{X_d^{\,2}}{2(1-X_d)} \tag{17}$$

for a M/D/1 queuing system as an approximation.



a) $Q_{in\text{-}turn}$=0.1

b) $Q_{in\text{-}turn}$=0.3

c) $Q_{in\text{-}turn}$=0.5

Figure 3. Upstream filtering adjustment factor *I* as a function of the upstream

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volume-to-capacity ratio X_u with the ratio of turning-in flow with a) $Q_{in\text{-}turn}$=0.1, b) $Q_{in\text{-}turn}$ =0.3, and c) $Q_{in\text{-}turn}$ =0.5 for different ratio of green time fu together with the results from the HCM formula

In Figure 3 the upstream filtering adjustment factor I is illustrated as a function of the upstream volume-to-capacity ratio X_u with the ratio of in-turning flow $Q_{in\text{-}turn}$=0.1, 0.3, and 0.5 for different proportion of green time f_u together with the results from the HCM formula. One can recognize that the HCM formula only represents the average value of possible situations. In most of cases under consideration there are significant differences between the HCM formula and the proposed model which takes the ratio of in-turning flow $Q_{in\text{-}turn}$ and the proportion of green time f_u into account.

If the upstream signal has coordinated upstream itself, then is

$$I = \frac{\left(1 - \frac{1 - f_u}{(1 - X_u f_u)(1 + Q_{in-turn})}\right)^2 \cdot K \cdot N_{free} + X_d}{N_{free} + X_d} \quad \text{with } K \le 1 \tag{18}$$

Normally, the factor K can be assumed being equal to 1 by default for a panning scenario. However, one can assume that the traffic flow will be increasingly bunch by series of coordinated signals. Assuming an independency between the signals yields $K = I^*$ of the next signal. Thus, for a signal with 2 upstream signals we have

$$I^{(2)} = \frac{\left(1 - \frac{1 - f_u^{(1)}}{(1 - X_u^{(1)} f^{(1)}{}_u)(1 + Q_{in-turn}{}^{(1)})}\right)^2 \left(1 - \frac{1 - f_u^{(2)}}{(1 - X_u^{(2)} f^{(2)}{}_u)(1 + Q_{in-turn}{}^{(2)})}\right)^2 N_{free} + X_d}{N_{free} + X_d} \tag{19}$$

And in general for a signal with m upstream signals is

$$I^{(m)} = \frac{\left[\prod_{j=1}^{m} \left(1 - \frac{1 - f_u^{(j)}}{(1 - X_u^{(j)} f^{(j)}{}_u)(1 + Q_{in-turn}{}^{(j)})}\right)\right] N_{free} + X_d}{N_{free} + X_d} \tag{20}$$

Determining progression adjustment factor

According to the methodology in HCM, the progression adjustment factor is defined by the equation

$$PF = \frac{1 - P}{1 - g/C} \tag{21}$$

with

$$P = R_p \frac{g}{C} \tag{22}$$

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where R_p is the so-called platoon ratio.

The platoon ratio R_p is used to describe the quality of signal progression for the corresponding movement group. It is computed as the demand flow rate during the green time divided by the average demand flow rate. Table 1 (cf. in HCM2010, Exhibit 18 - 8) provides an indication of the quality of progression associated with selected platoon ratio values.

Table 1. Relationship between Arrival Type and Progression Quality

Platoon Ratio R_p	**Arrival Type**	**Progression Quality**
0.33	1	Very poor
0.67	2	Unfavorable
1.00	3	Random arrivals
1.33	4	Favorable
1.67	5	Highly favorable
2.00	6	Exceptionally favorable

The platoon ratio R_p can be judged from the table above by using the arrival type designation. Values of arrival type range from 1 to 6. A description of each arrival type is provided in the HCM as following.

Arrival type 1 is characterized by a dense platoon of more than 80 percent of the movement group volume arriving at the start of the red interval.

Arrival type 2 is characterized by a moderately dense platoon arriving in the middle of the red interval or a dispersed platoon containing 40 to 80 percent of the movement group volume arriving throughout the red interval.

Arrival type 3 describes one of two conditions. If the signals bounding the segment are coordinated, then this arrival type is characterized by a platoon containing less than 40 percent of the movement group volume arriving partially during the red interval and partly during the green interval. If the signals are not coordinated, then this arrival type is characterized by platoons arriving at the subject intersection at different points in time over the course of the analysis period such that arrivals are effectively random.

Arrival type 4 is characterized by a moderately dense platoon arriving in the middle of the green interval or a dispersed platoon containing 40 to 80 percent of the movement group volume arriving throughout the green interval. This arrival type is often associated with segments of average length with favorable progression in the subject direction of travel.

Arrival type 5 is characterized by a dense platoon of more than 80 percent of the movement group volume arriving at the start of the green interval.

Arrival type 6 is characterized by a dense platoon of more than 80 percent of the movement group volume arriving at the start of the green interval.

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Obviously, the platoon ratio R_p is dependent on the proportion P_{pl} of vehicles in platoon und on the arriving time t_a of the platoon within a cycle. The HCM doesn't provide any methodology for calculating the proportion of vehicles in platoon. Fortunately, for the default case in a planning scenario, the proportion P_{pl} of vehicles in platoon can be given here as (see above)

$$P_{pl} = \frac{(1-f_u)}{(1-X_u f_u)(1+Q_{in-turn})} \qquad (23)$$

According the description of the arrival types in HCM, the relationship between the platoon ratio as a function of the proportion P_{pl} of vehicles in platoon and the arriving time t_a of the platoon can be established. Table 2 shows the values of the platoon ratio according to the HCM description. Unfortunately, the HCM description for the 6 arrival types (T1-T6) does not fill out the whole matrix. The empty cells of the table are filled here with the average values (black bold numbers) calculated from the values in the nearby cells.

Table 2. Values of platoon ratio R_p according to the HCM description

arriving time of the platoon t_a	Proportion P_{pl} of vehicles in platoon			
	40%	60%	80%	100%
0.0R(1.0G) [1)]	1,00 (T3)	**0,83**	0,33 (T1)	0,00
0.5R [2)]	1,00 (T3)	0,67 (T2)	**0,92**	1,00
1.0R(0.0G) [3)]	1,00 (T3)	**1,17**	1,67 (T5)	2,00 (T6)
0.5G [4)]	1,00 (T3)	1,33 (T4)	**1,08**	1,00
1.0G(0.0R) [5)]	1,00 (T3)	**0,83**	0,33 (T1)	0,00

[1)] At the beginning of red interval (= at the end of green interval)
[2)] In the middle of red interval
[3)] At the beginning of green interval (= at the beginning of green interval)
[4)] In the middle of green interval
[5)] At the end of green interval (= at the beginning of red interval), corresponds to [1)]

The platoon ratio R_p can also be estimated using the following monograph (Figure 4).

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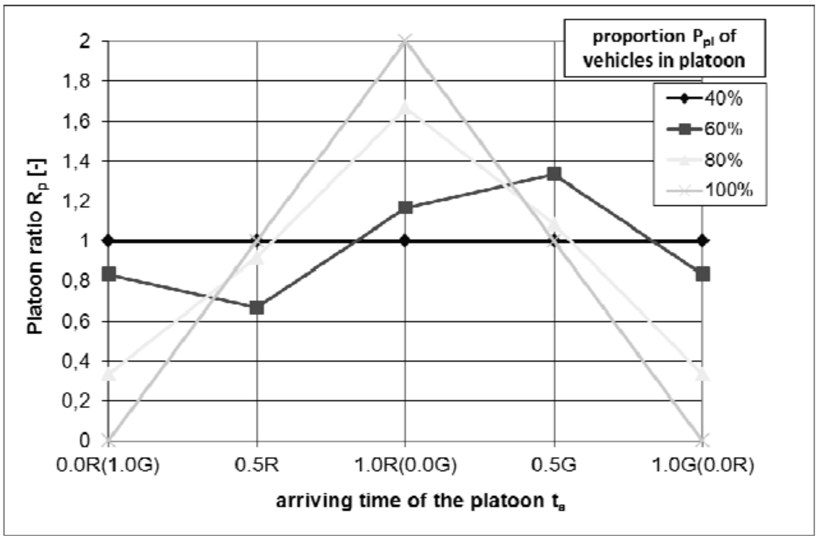

Figure 4. Platoon ratio R_p as a function of the proportion of vehicles in platoon P_{pl} and the arriving time of the platoon t_a

For other P_{pl} and t_a values the platoon ratio R_p can be interpolated using Table 2 or Figure 4.

CONCLUSIONS

For calculating the progression adjustment factor and the upstream filtering adjustment factor at signalized intersections, two simple approaches are introduced. The new approaches are generalizations of the existing HCM procedures. According to the new approaches, the upstream filtering adjustment factor is a function of the upstream volume-to-capacity ratio, the proportion of upstream green time, and the in-turning flow rate from the side roads; the platoon ratio is defined by the proportion of vehicles in platoon and the arriving time of the platoon within the cycle length. With the new approaches, the delays at coordinated signals can be more accurately estimated for default conditions in planning sceneries.

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