Modifying Progression Adjustment Factor and Upstream Filtering Adjustment Factor at Signalized Intersections in HCM

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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, namely the progression adjustment factor and 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 HCM.

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

INTRODUCTION

In 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 in the platoon. This can reduce the cycle failure frequency and the resulting delay.

In 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.

For determining the upstream filtering adjustment factor, 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 upstream green time ratio and on the in-turning volume 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 HCM.

DELAY ESTIMATION IN HCM

In 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	=	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 the cycle failure frequency and the resulting delay.

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

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

with

$$PF = \frac{1-P}{1-g/C} \qquad (3)$$

where

d_1 = uniform delay d_1, s
PF = progression adjustment factor, -
P = proportion of vehicles arriving on green, -
g/C = green time ratio, -
g = green time length, s
C = cycle time length, 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. In HCM, the following equation is used to compute upstream filtering adjustment factor I for non−isolated intersections (HCM 2010, Equation 18-3).

$$I = 1.0 - 0.91 X_u^{2.68} \geq 0.090 \qquad (4)$$

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:

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

with

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

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

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

$P_{u,pl}$ = proportion of the bunched (in platoon) upstream vehicles, -
X_d = downstream volume-to-capacity ratio, -

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

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

and again

$$P_{u,free} = 1 - P_{u,pl} \tag{10}$$

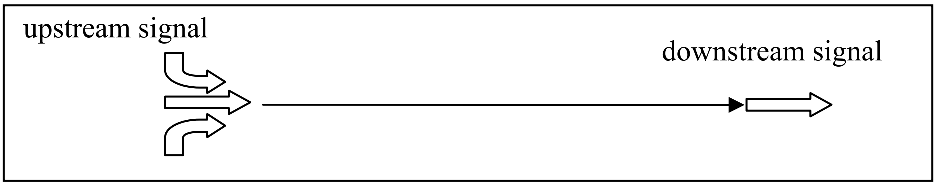


Figure 1 - Possible upstream streams

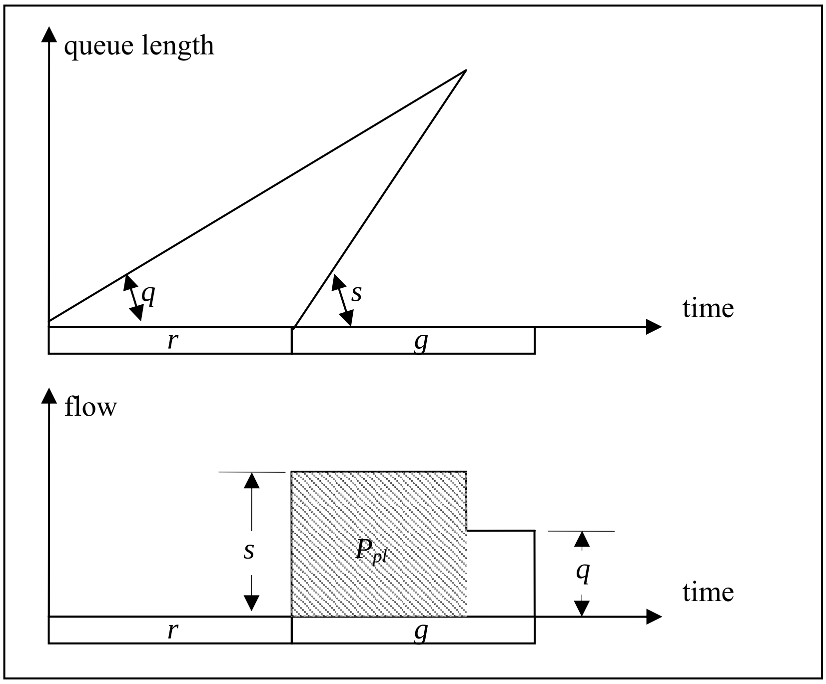


Figure 2 - Proportion of platoon P_{pl} (g = green time length, r = C - g = red time length, q = flow rate, s = saturation flow rate)

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 upstream vehicles at an isolated upstream intersection is (see 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 green time ratio in the i-th upstream stream. 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 stream with bunched vehicles, is

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

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

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

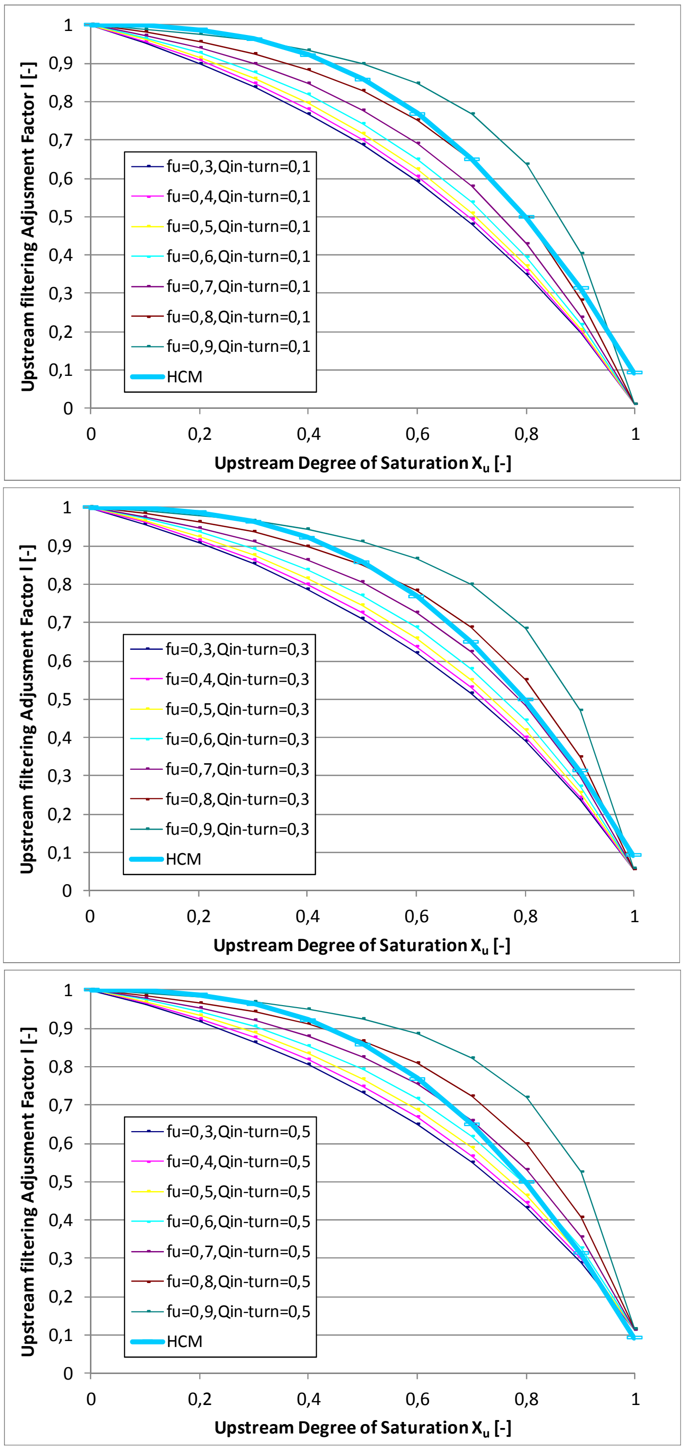
$$\begin{aligned} P_{u,free} &= \frac{M_{free}}{M_u + M_{in-turn}} = \frac{M_u \frac{f_u (1 - X_u)}{1 - X_u f_u} + M_{in-turn}}{M_u + M_{in-turn}} = \frac{q_u \frac{f_u (1 - X_u)}{1 - X_u f_u} + q_{in-turn}}{q_u + q_{in-turn}} \\ &= \frac{\frac{f_u (1 - X_u)}{1 - X_u f_u} + \frac{q_{in-turn}}{q_u}}{1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

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

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

$q_{in-turn}$ = in-turning volume, vhe/h

q_u = upstream volume, vhe/h



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 volume-to-capacity ratio X_u with the ratio of turning-in flow: 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 f_u together with the results from the HCM formula

Thus, for this very common case is

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

with

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

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

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 green time ratio f_u together with the results from the HCM formula. One can recognize that the HCM formula only represents approximately 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 green time ratio f_u into account.

With eq. (17) eq. (16) can be rewritten as

$$I = \frac{I^* N_{free} + X_d}{N_{free} + X_d} = \frac{\left(1 - \frac{1 - f_u}{(1 - X_u f_u)(1 + Q_{in-turn})}\right)^2 X_d + 2(1 - X_d)}{2 - X_d} \tag{18}$$

If the upstream signal has coordinated upstream itself, then is

$$I = \frac{\left(1 - \frac{1 - f_u}{(1 - X_u f_u)(1 + Q_{in-turn})}\right)^2 \cdot K \cdot N_{free} + X_d}{N_{free} + X_d} \quad \text{with } K \le 1 \tag{19}$$

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 approximately

$$I^{(2)} = \frac{\left(1 - \frac{1 - f_u^{(1)}}{(1 - X_u^{(1)} f^{(1)}{}_u)(1 + Q_{in-turn}{}^{(1)})}\right)^2 \left(1 - \frac{1 - f_u^{(2)}}{(1 - X_u^{(2)} f^{(2)}{}_u)(1 + Q_{in-turn}{}^{(2)})}\right)^2 N_{free} + X_d}{N_{free} + X_d} \tag{20}$$

And in general for a signal with *m* upstream signals is

$$I^{(m)} = \frac{\left[\prod_{j=1}^{m}\left(1 - \frac{1 - f_u^{(j)}}{(1 - X_u^{(j)} f^{(j)}_u)(1 + Q_{in-turn}^{(j)})}\right)^2\right] N_{free} + X_d}{N_{free} + X_d} \quad (21)$$

Determining Progression Adjustment Factor

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

$$PF = \frac{1 - P}{1 - g/C}, \text{ subject to } 0 \le PF \le 1 \quad (22)$$

with

$$P = R_p \frac{g}{C} \quad (23)$$

where R_p is the so-called platoon ratio.

The progression adjustment factor *PF* descript actually the ratio between the delay with steady-state arrivals and the delay with platooned arrivals under the condition of progression.

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. HCM (cf. Exhibit 18−8 in HCM2010) provides an indication of the quality of progression associated with selected platoon ratio values (Table 1).

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 1 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.

Obviously, the platoon ratio R_p is dependent on the proportion P_{pl} of vehicles in platoon und on the arriving time of the platoon, t_a, within a cycle. 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 the previous section, eq.(15))

$$P_{pl} = \frac{(1 - f_u)}{(1 - X_u f_u)(1 + Q_{in-turn})} \tag{24}$$

According the description of the arrival types in HCM, the relationship between the platoon ratio as a function of the proportion of vehicles in platoon, P_{pl}, 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 of vehicles in platoon, P_{pl}			
	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). For other P_{pl} and t_a values the platoon ratio R_p can be interpolated using Table 2 or Figure 4.

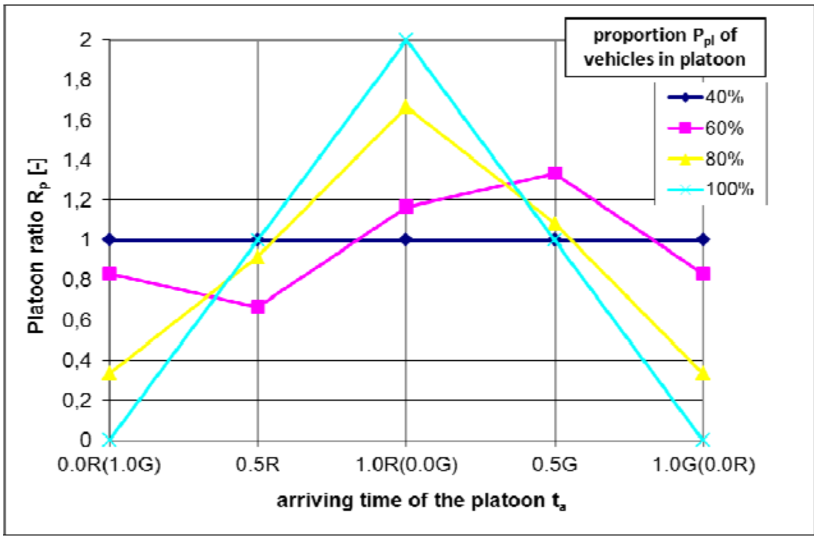


Figure 4 - Platoon ratio R_p as a function of the proportion of vehicles in platoon, P_{pl}, and the arriving time of the platoon, t_a

Unfortunately, as seen in Figure 8, the curves for the platoon ratio R_p based on the data in HCM show some stranger shapes and discontinuities. One can question the accuracy of the graph and the values in Table 2. Here, one should take a near look at the derivation. In general, the platoon ratio R_p can be derived by comparing the uniform delay d_1 under steady-state arrivals with that under coordinated condition with platoons.

The uniform delay is the delay caused by changing signal phases from green to red or vice versa. It is only depends on the deterministic arrival patterns and not on the stochastic properties of arrivals. For example, the first term of the Webster's delay formula gives the uniform delay with a steady-state arrival pattern as follows:

$$d_{1,st} = \frac{(1 - g/C)^2}{2(1 - g/C \cdot X)} C \tag{25}$$

For platooned arrivals the formulation of the uniform delay is more complicated. The uniform delay is in general a function of the degree of saturation *X*, the green time length *g*, the cycle tine length *C*, the ratio of platoon P_{pl}, the flow rate in the platoon, q_2, the flow rate outside of the platoon, q_1, the saturation flow rate *s*. and certainly the arriving time of the platoon, t_a (cf. Figure 5). According to the queue development illustrated in Figure 5, a generalized but very comprehensive formulation for the uniform delay d_1 can be derived regarding all of those parameters. The derivations can be verified by simulations studies. The formulation is not given here because of the complexity and limited space in the paper. The formulation can be obtained by the author if required.

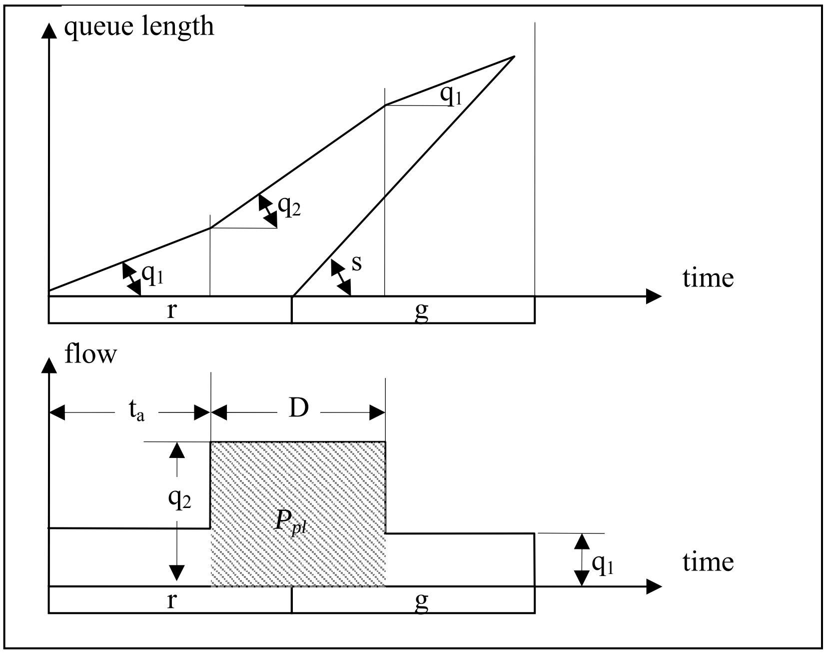


Figure 5 - Proportion of platoon P_{pl} and the corresponding queue length for calculation uniform delay d_1

It is always true due to definition:

$$P_{pl} = \frac{q_2 \cdot D}{q \cdot C} \quad \text{or} \quad q \cdot C = \frac{q_2 \cdot D}{P_{pl}} \tag{26}$$

where *D* is the length in time for the platoon.

Please note in all formulations for the uniform delay d_1 the expression D/C can be replaces by

$$\frac{D}{C} = P_{pl} \cdot \frac{q}{q_2} = P_{pl} \cdot \frac{s}{q_2} \cdot \frac{g}{C} \cdot X \qquad (27)$$

Thus, the parameter D can be totally eliminated from the formulation.

The progression adjustment factor PF and the platoon ratio R_p can be obtained according to the definitions:

$$PF = \frac{d_1}{d_{1,st}} \qquad (28)$$

and

$$R_p = \frac{1 - PF \cdot (1 - g/C)}{g/C} \qquad (29)$$

The functions of PF and R_p can be normalized to the ratios X, P_{pl}, g/C, q_2/s, and t_a/C. That is, we have generally

$$PF = f(X, P_{pl}, \frac{q}{C}, \frac{q_2}{s}, \frac{t_a}{C}) \text{ and } R_p = f(X, P_{pl}, \frac{q}{C}, \frac{q_2}{s}, \frac{t_a}{C}) \qquad (30)$$

In Figure 6 the progression adjustment factor PF and the platoon ratio R_p as functions of t_a/C and P_{pl} with constant values X=0.9, q_2/s=0.9, and g/C=0.5 are illustrated. One can recognize clearly the similarity and differences from Figure 6b to Figure 4. A set of monographs were produced for all parameter combinations. These monographs can also be obtained by the author if required.

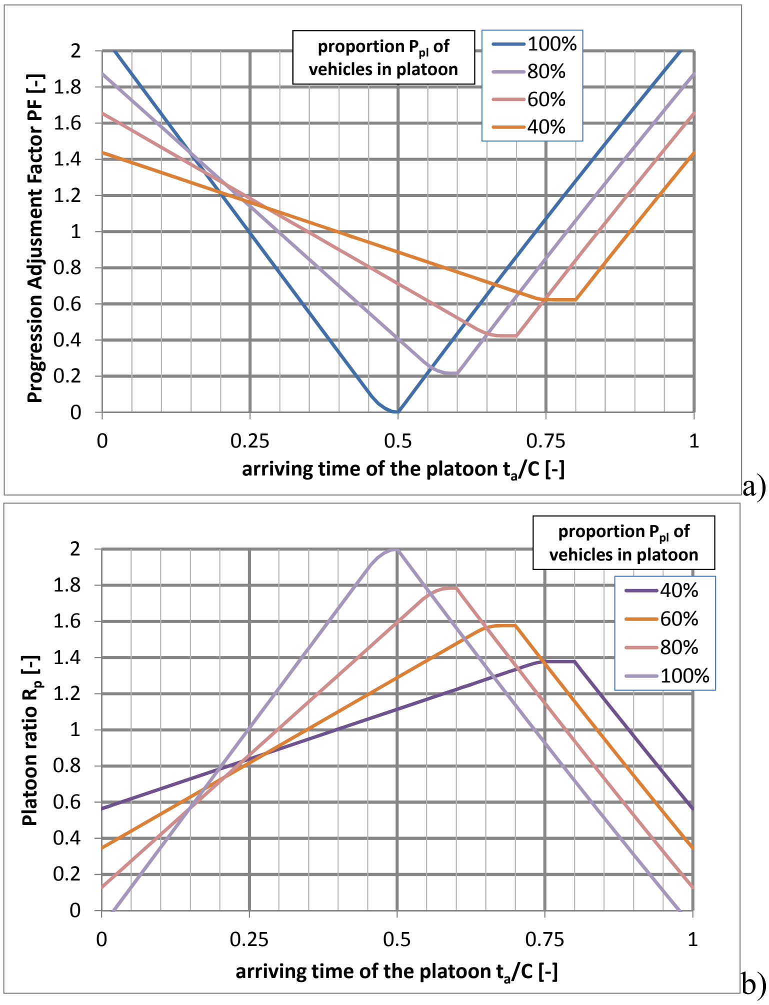


Figure 6 - *PF* (a) and R_p (b) as functions of t_a/C and P_{pl} with constant values X=0.9, q_2/s=0.9, and g/C=0.5

For simplifying the formulation of the progression factor *PF* and platoon ratio R_p we consider now the case X=1. That is the worst case under consideration regarding delay analyses. This is a significant, but needed simplification in order to get rid of the complicated formulations.

For this special case we have always $q \cdot C = s \cdot g$ and the uniform delay can be calculated according to the illustration in Figure 5 as following.

For $t_a + D < C$ is

$$d_{1a}=\frac{\frac{q_2\cdot D^2}{2}+\frac{q_2\cdot D+s\cdot g}{2}(C-D)-q_2\cdot D\cdot t_a-\frac{s\cdot g}{2}\cdot g}{q\cdot C}$$

$$=\frac{\frac{(\frac{D}{C})^2}{2}+\frac{\frac{D}{C}+\frac{s}{q_2}\cdot\frac{g}{C}}{2}(1-\frac{D}{C})-\frac{D}{C}\cdot\frac{t_a}{C}-\frac{s\cdot(\frac{g}{C})^2}{2q_2}}{\frac{D}{C}}\cdot P_{pl}\cdot C \tag{31}$$

For $t_a+D\geq C$ is

$$d_{1b}=\frac{\frac{q_2\cdot D^2}{2}+\frac{s\cdot g-q_2\cdot D}{2}(C-D)-\frac{s\cdot g}{2}\cdot g+q_2(C-D)(t_a-(C-D))}{q\cdot C}$$

$$=\frac{\frac{(\frac{D}{C})^2}{2}+\frac{\frac{s}{q_2}\cdot\frac{g}{C}-\frac{D}{C}}{2}(1-\frac{D}{C})-\frac{s\cdot(\frac{g}{C})^2}{2q_2}+(1-\frac{D}{C})(\frac{t_a}{C}-(1-\frac{D}{C}))}{\frac{D}{C}}\cdot P_{pl}\cdot C \tag{32}$$

Please note in both equations the expression D/C can be replaces by

$$\frac{D}{C}=P_{pl}\cdot\frac{s}{q_2}\cdot\frac{g}{C} \tag{33}$$

due to the predefined condition of X=1. Thus, the parameter D can be eliminated.

The final expression of the uniform delay for X=1 is,

$$d_1=\max(d_{1a,}\ d_{1b}) \tag{34}$$

The progression factor is then

$$PF=\frac{d_1}{d_{1,st}} \tag{35}$$

with

$$d_{1,st}=\frac{(1-g/C)^2}{2(1-g/C\cdot X)}C\,|_{X=1}=\frac{C-g}{2} \tag{36}$$

And the platoon ratio is

$$R_p = \frac{1 - PF \cdot (1 - g/C)}{g/C} \tag{37}$$

For an additional simplification we can assume q_2=s (normally, it is almost the case in the reality). Thus,

$$P_{pl} = \frac{q_2 \cdot D}{q \cdot C} = \frac{q_2 \cdot D}{s \cdot g} = \frac{D}{g} \quad \text{and} \quad \frac{D}{C} = P_{pl} \frac{g}{C} \tag{38}$$

The result of the assumptions X=1 and q_2=s is a two-piece linear function for the platoon ratio R_p regarding the ratio t_a/C. Rearranging the equations above yields the following final simple equation:

$$R_p = \min \begin{cases} (1 - P_{pl}) + \dfrac{2}{1/P_{pl} - g/C} \dfrac{t_a}{C} \\ (1 - P_{pl}) + \dfrac{2}{g/C}(1 - \dfrac{t_a}{C}) \end{cases} \tag{39}$$

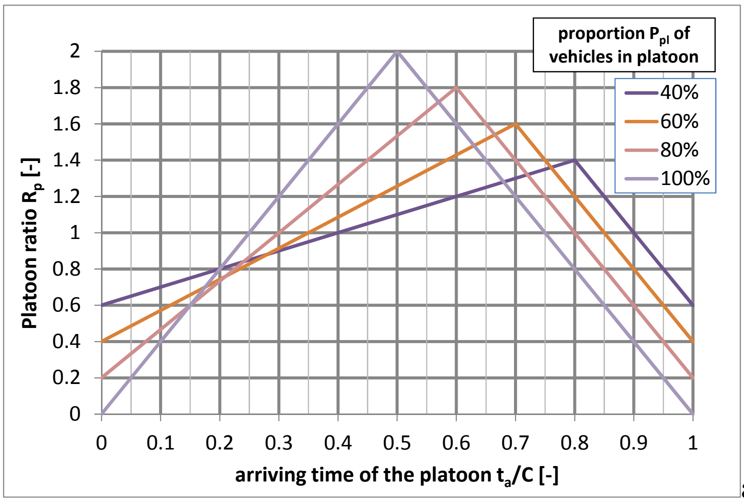
The intersection point of the two function branches gives the maximum value of R_p and it indicates the best offset of the platoon with minimized delay. This point can be obtained by setting d_{1a}=d_{1b}. The intersection point is defined by

$$\frac{t_a}{C} = 1 - P_{pl} \cdot g/C \tag{40}$$

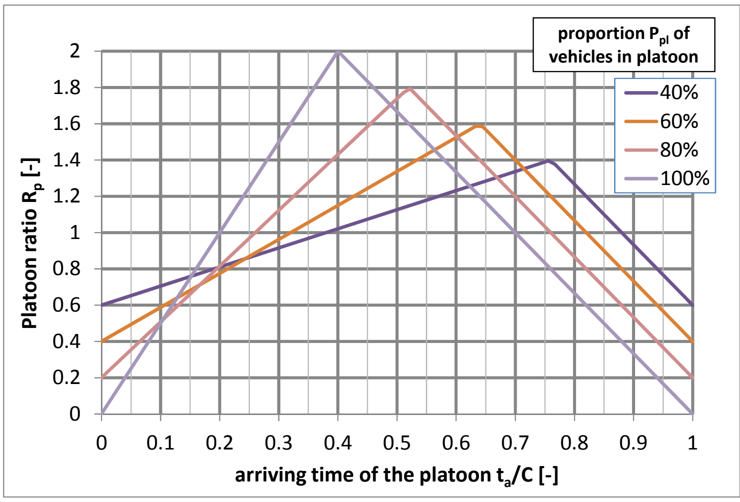
and

$$R_{p,\max} = 1 + P_{pl} \tag{41}$$

The value of R_p depends on the green ratio g/C. Figure 7 shows two examples for g/C=0.5 and g/C=0.6. Comparing Figure 7a with Figure 6b one can recognize, that the pictures (both for g/C=0.5) deliver very similar values for the platoon ratio R_p. That means, the simplifications X=1 and q_2/s=1 do not significantly change the values of the platoon ratio R_p.



a)



b)

Figure 7 - R_p as functions of t_a/C and P_{pl} with constant values X=1 and q_2/s=1
a) g/C=0.5; b) g/C=0.6

Moreover, both pictures in Figure 7 show a very similar structure on the left and right side of $t_a/C = r/C = 1 - g/C$. That is, the function R_p has always a similar shape when the platoon arrives within the red time interval or within the green time interval respectively regardless of the value of g/C. For setting up a simple approach for practitioners we can re-scale the x-axis in two branches for red time and green time in Figure 7b). The result of the re-scaled graph is shown in Figure 8.

Figure 8 is constructed in the same way as Figure 4 (corresponding to the values in Table 1). Obviously, this picture has a more plausible structure than Figure 4. Thus, Figure 8 is recommended now in place Figure 4 (cf. Table 1 and Exhibit 18‒8 in HCM2010). Figure 8 can be constructed by setting g/C=0.5. Thus, the equation for Figure 8 can be defined as

$$R_p = \min \begin{cases} (1-P_{pl}) + \dfrac{4}{2/P_{pl}-1}\dfrac{t_a}{C} \\ (1-P_{pl}) + 4(1-\dfrac{t_a}{C}) \end{cases} \quad (42)$$

The factor t_a/C is now defined as the proportion of the green time (G) or the red time (R).

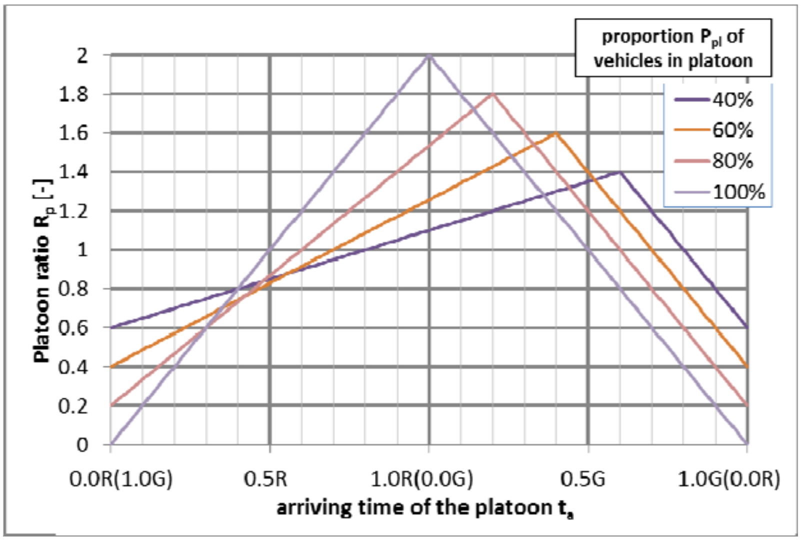


Figure 8 - Simplified graph for estimation the platoon ratio R_p as a function of the proportion of vehicles in platoon P_{pl} and the arriving time of the platoon t_a

CONCLUSIONS

For calculating the progression adjustment factor and the upstream filtering adjustment factor at signalized intersections, two simple models are introduced in order to modify the approaches in HCM. The new models are generalizations of the existing HCM procedures. According to the new models, the upstream filtering adjustment factor is a function of the upstream volume-to-capacity ratio, the upstream green time ratio, and the in-turning volume from the side roads. The progression adjustment factor can be defined by the equation (16). The platoon ratio is a function of the proportion of vehicles in platoon, the green time ratio, and the arriving time of the platoon within the cycle length. The platoon ratio can be defined by the equation (39). With the new models, the delays at coordinated signals can be more accurately estimated for default conditions in planning sceneries.

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