

# PERFORMANCE POTENTIAL OF SIGNALIZED ARTERIALS AND INTERSECTIONS

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## ABSTRACT

Intersection capacity is a scarce resource which needs to be allocated economically. Traffic control at signalized intersections involves balancing competing demands of conflicting traffic streams for limited capacity at the intersection. Similarly, progression schemes on two-way arterial streets involve a compromise between the demands of opposing and competing traffic streams along the arterial. In both cases there is a tradeoff between the performance advantages that each traffic stream can enjoy and there is a need for a tool to assess the performance potential of the signals. This phenomenon is akin to tradeoffs in production capabilities of economic systems that gives rise to the well-known *Production Potential Frontier*. We introduce similar concepts for signalized intersections and coordinated arterial streets. We call them the *Transition Potential Frontier* (TPF) and the *Progression Potential Frontier* (PPF), respectively. We then introduce a number of criteria to assess the performance of signalized intersections and arterials using the *Level-of-Service* (LOS) concept. These criteria lead to rational design and evaluation procedures which are essential in obtaining the best performance from the traffic signals.

*Keywords: Traffic Signals, Signal Control, Coordination, Quality of Progression, Level-of-Service*

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## INTRODUCTION

Effective signal control policies are a major factor in improving mobility and in reducing congestion in urban areas. Proper design and evaluation procedures are essential for optimizing the performance of urban arterial streets<sup>1</sup>. This paper presents new tools for assessing the performance of signalized intersections and arterial street systems. These tools can be used for more effective evaluation and design which are necessary for optimizing the performance of urban streets.

The most valuable resource in an urban network is the intersection capacity. Traffic signal controls are often the determining factor in the functioning of urban street systems because they enable the effective utilization of this resource. The paper introduces the concept of a *Performance Potential Frontier*, akin to the *Production Potential Frontier* (PPF) in economic systems (Samuelson and Nordhaus, 1980). This concept enables one to evaluate the tradeoffs in performance that exist when we have competing demands for limited resources. In case of an isolated signalized intersection the tradeoff is between the capacities allocated to the competing traffic streams by the green splits. We call this performance potential frontier the *Transition Potential Frontier*. In the case of urban arterial streets, where signal coordination is concerned, it is called the *Progression Potential Frontier*.

Signal coordination has a major impact on the performance of arterial streets with signalized intersections. The U.S. *Highway Capacity Manual* (HCM) provides the most widely used procedures for *Level-of-Service* (LOS) analysis in the USA (TRB, 2000). Similar concepts have also been adopted in other countries. The HCM uses average control delay per vehicle as the Measure of Effectiveness (MOE) for signalized intersections. The LOS for arterial streets is based on the Average Travel Speed on the arterial and the arterial street classification. The average travel speed is computed from the length of the street segments and the running times, which includes control delay of through movements at the signalized intersections. Accurate estimation of delay at signalized intersections is an important factor in arterial street performance analysis.

Quality of Progression plays an important role in performance evaluation of arterial streets. Various studies have shown deficiencies in the existing HCM procedures to adequately take into account the effects of coordination or lack of it. Gartner and Deshpande (2009a) developed procedures for accurate representation of Quality of Progression on arterial streets. They introduced new approaches for the assessment of the LOS on an arterial incorporating systematic accounting of the effects of coordination. They employ a *Cyclic Coordination Function* (CCF) and a corresponding *Coordination Adjustment Factor* (CAF) to quantify the quality of progression in conjunction with the HCM delay estimation procedure. The following alternative yet interrelated approaches are presented:

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<sup>1</sup> The notion of “arterial street” implies a street with coordinated signal-controlled intersections.

- a. *Coordination Adjustment Factor* as a performance measure for Quality of Progression.
- b. Level-of-Service analysis using average delay for the arterial street in its entirety.
- c. Level-of-Service analysis using the average travel speed incorporating coordination effects.

## PERFORMANCE ASSESSMENT AT SINGLE INTERSECTIONS

The HCM defines control delay as the portion of the total delay for a vehicle approaching and entering a signalized intersection that is attributable to traffic signal operations. Control delay includes delays of initial deceleration, move-up time in queue, stops, and reacceleration (TRB, 2000).

The control delay is calculated as follows:

$$d = d_1 * (PAF) + d_2 + d_3 \quad (1)$$

$$d_1 = \frac{0.5C \left(1 - \frac{g}{C}\right)^2}{1 - \left[\min(1, X) * \frac{g}{C}\right]} \quad (2)$$

$$d_2 = 900T \left[ \left( X - 1 \right) + \sqrt{\left( X - 1 \right)^2 + \frac{8kIX}{cT}} \right] \quad (3)$$

where,

- $d$  = control delay (s/veh);
- $d_1$  = uniform delay (s/veh);
- $d_2$  = incremental delay (s/veh);
- $d_3$  = initial queue delay (s/veh);
- $PAF$  = progression adjustment factor;
- $X$  = volume to capacity (v/c) ratio for the lane group (also termed degree of saturation);
- $C$  = cycle length (s);  $g$  = effective green time for lane group (s);
- $c$  = capacity of lane group (veh/h);
- $T$  = duration of analysis period (h);
- $k$  = incremental delay adjustment for the actuated control; and
- $l$  = incremental delay adjustment for the filtering or metering by upstream signals.

Terms in the control delay equation are:

- $d_1$ , *Uniform delay* gives an estimate of control delay assuming perfectly uniform arrivals and a stable flow. It is based on the first term of Webster's delay formulation.

- $d_2$ , *Incremental delay* is due to non-uniform arrivals and individual cycle failures (i.e., random delay) as well as delay caused by temporary periods of over-saturation (i.e., over-saturation delay).
- $d_3$ , *Initial queue delay* is the delay experienced by newly arrived vehicles, when a queue from the previous period is present at the start of the analysis.
- *PAF, Progression factor* takes into account effects of coordination; in the case of an isolated signal, PAF = 1.0.

An illustration of the HCM delay as a function of the degree of saturation is shown in Fig. 1. The HCM associates a *Level of Service* (LOS) designation with the different delay ranges from A to F. This is shown in Table 4 below.

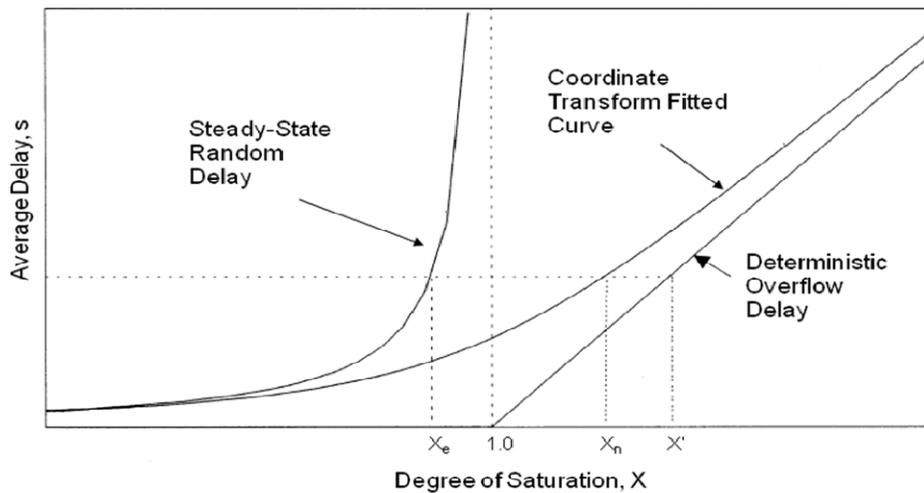


Figure 1 – Control delay as a function of degree of saturation.

## PERFORMANCE ASSESSMENT FOR SIGNALIZED ARTERIAL STREETS

The HCM arterial street methodology is used to analyze urban and suburban streets with traffic signal spacings of 2 miles or less. The effects of coordination or progression diminishes at greater signal spacings due to traffic dispersion along the arterial. Both one-way and two-way streets can be analyzed with this methodology. Each travel direction of the two-way street requires a separate analysis. The HCM methodology uses Average Travel Speed for measuring the performance of an arterial.

The Average Travel Speed is computed from the running times on the street segments and the control delay of through movements at the signalized intersections. HCM has four different arterial street classes depending on the Free-Flow Speed (FFS) range. The LOS can be determined by the Average Travel Speed and Urban Street Class, as shown in Table 1. The running time is dependent upon

the street's classification. Within the classification, the running time is also affected by length of the segment, presence of parking, side friction, local development and street use.

The effect of progression is taken into account by the *Progression Adjustment Factor* (PAF) in Eqn. (1) which estimates the control delay. The measure of effectiveness (MOE) for signalized intersection LOS is the average control delay per vehicle. An accurate estimation of control delay is thus essential for correct performance evaluation.

Table 1 – LOS Criteria for Urban Streets (HCM 2000)

EXHIBIT 15-2. URBAN STREET LOS BY CLASS

Urban Street Class	I	II	III	IV
Range of free-flow speeds (FFS)	55 to 45 mi/h	45 to 35 mi/h	35 to 30 mi/h	35 to 25 mi/h
Typical FFS	50 mi/h	40 mi/h	35 mi/h	30 mi/h
LOS	Average Travel Speed (mi/h)			
A	> 42	> 35	> 30	> 25
B	> 34-42	> 28-35	> 24-30	> 19-25
C	> 27-34	> 22-28	> 18-24	> 13-19
D	> 21-27	> 17-22	> 14-18	> 9-13
E	> 16-21	> 13-17	> 10-14	> 7-9
F	≤ 16	≤ 13	≤ 10	≤ 7

### Quality of Progression

A critical characteristic that must be quantified for the analysis of an urban street or signalized intersection is the *Quality of Progression* (QOP). The parameter that describes this characteristic in the HCM is the arrival type, AT. This parameter approximates the Quality of Progression by defining six types of dominant arrival flow (Table 2).

Table 2 – Arrival Type and Progression Quality (HCM 2000)

EXHIBIT 15-4. RELATIONSHIP BETWEEN ARRIVAL TYPE AND PLATOON RATIO ( $R_p$ )

Arrival Type	Range of Platoon Ratio ( $R_p$ )	Default Value ( $R_p$ )	Progression Quality
1	≤ 0.50	0.333	Very poor
2	> 0.50-0.85	0.667	Unfavorable
3	> 0.85-1.15	1.000	Random arrivals
4	> 1.15-1.50	1.333	Favorable
5	> 1.50-2.00	1.667	Highly favorable
6	> 2.00	2.000	Exceptional

*Quality of Progression* (QOP) is an indication of the favourability or un-favourability of the movement of platoons through succeeding intersections. As can be seen from Eqn. 1, the uniform delay is multiplied by the *Progression Adjustment Factor* (PAF) to account for coordination. A favourable coordination scheme has a PAF value of less than 1, reducing overall delay. An unfavourable coordination has a PAF value of greater than 1, resulting in an increase in overall delay. PAF has a strong bearing on

the calculation of control delay and determination of overall LOS of the arterial. Since  $R_p$  (and PAF). Studies have shown limitations of the PAF to adequately take into account the effects of coordination or lack of it. This may result in significant under- or over-estimation of delay.

The PAF is represented by the Platoon Ratio  $R_p = P(C/g)$ , where  $P$  is the proportion of vehicles arriving during green, as shown in Table 2. The HCM suggests that arrival type can be determined by approximating a time-space diagram or by using field observations. There are six distinct arrival types depending on traffic conditions. Arrival Types 1-2 represent unfavourable coordination while 4-6 represent favourable coordination. Arrival Type 3 is for random arrivals, when there are no effects of coordination. The six distinct arrival types cannot account accurately for the multitude of arrival scenarios that can occur on a signalized arterial. In particular, the procedure does not explicitly consider the effects of offsets on feeder links. The offset on a feeder link (i.e., at the upstream intersection) can have a significant effect on the delay at the current intersection at low and medium volumes. At such volumes, succinct platoons may proceed under favourable progression unimpeded to the next segment, whereas when progression is unfavourable their path will be blocked at the downstream intersection. This causes an increase in delay. When volumes are higher ( $v/c \geq 0.90$ ) this phenomenon is masked since platoons are already impeded at the upstream intersection for virtually all offsets on prior segments. This phenomenon is further attenuated by the degree of dispersion, i.e., greater dispersion will diminish the effect. A detailed analysis is given by Gartner and Deshpande (2009b).

## CYCLIC COORDINATION FUNCTION

In this section we describe an alternative approach for assessment of coordination effects in the control delay equation. This approach supplants the HCM *Progression Adjustment Factor* (PAF) model with a *Coordination Adjustment Factor* (CAF) which is based on a periodic, continuously variable function termed *Cyclic Coordination Function* (CCF). The *Cyclic Coordination Function* measures delay or travel time as a function of offsets along a signalized section of street (also called *link*). If the signals at the ends of the link are coordinated and synchronized (i.e., have the same cycle time), the function is continuous and periodic with the (common) cycle time. Being periodic with the cycle time the *Cyclic Coordination Function* can be modelled as a *Fourier Series* which is an expansion of a periodic function  $f(x)$  in terms of a sum of sines and cosines. This is called *harmonic analysis* and the individual components are called *harmonics*. A limited number of harmonics can provide good approximations to the original functions. The *Coordination Adjustment Factor* (CAF) is derived from the CCF and is defined as the ratio of the value of this function at a particular point (i.e., delay at a given offset) and the underlying average delay (i.e., the uncoordinated delay), as follows:

$$\text{Coordination Adjustment Factor} = \frac{\text{Delay at Given Offset (CCF)}}{\text{Average Delay}} \quad (4)$$

The CCF (and thereby the CAF) depends on a variety of factors, including: traffic flow characteristics, link physical characteristics, and traffic signal controls. The CAF can then be used in place of the existing PAF in the HCM control delay equation; thus Eqn. (1) now reads as follows:

$$d = d_1 * (CAF) + d_2 + d_3 \tag{5}$$

Figure 2 shows the delay vs. offset relationship for a pair of intersections and the cyclic coordination factor values for an example scenario (cycle length for this example is 100s). CAF values are higher than 1.0 for unfavourable coordination and below 1.0 for favourable coordination.

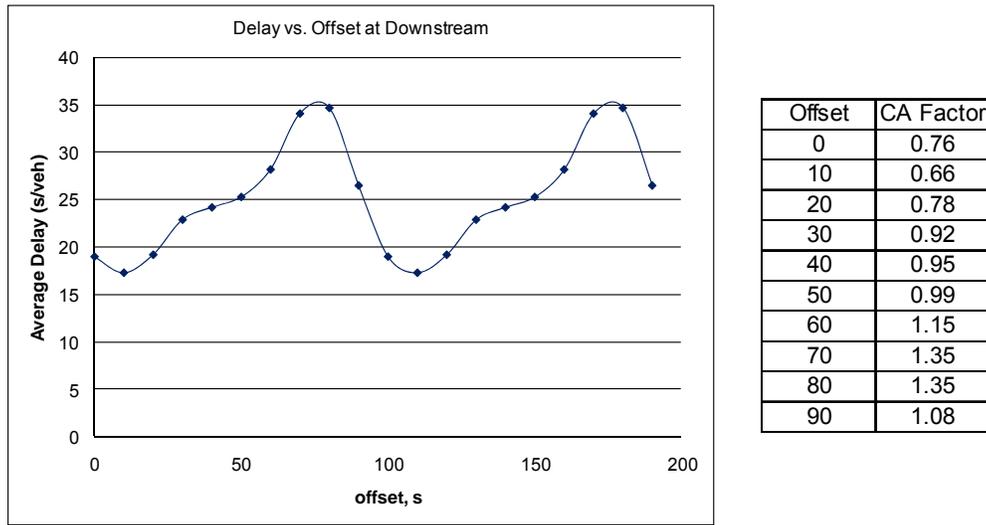


Figure 2 – Coordination Adjustment Factors.

The Cyclic Coordination Function can be generated by a variety of traffic models such as TRANSYT-7F (McTrans, 2006), Synchro (Husch, 2003) or CORSIM (ITT Industries, 2001). The CCF can also be modelled as a *Fourier Series* and can be derived analytically by estimating its Fourier components from traffic and link data alone. Such model can be executed as simply as by an excel spreadsheet (Gartner and Deshpande, 2009a).

## LEVEL-OF-SERVICE AND QUALITY OF PROGRESSION MODELS

In this section we present three alternative ways of assessing the QOP on an arterial street :

- (a) using the average CAF value as a performance measure for QOP

- (b) determining LOS using the average delay on the entire arterial, and
- (c) LOS determination using average travel speed computed with coordination.

### Using the Coordination Adjustment Factor as Performance Measure for Quality of Progression

The Coordination Adjustment Factor, which was previously used to characterize the Quality of Progression on a single link, can be further extended to develop a new procedure for assessing the Quality of Progression on an arterial. The impedance to the movement of vehicles along the arterial reflected in the values of the *Coordination Adjustment Factor* (CAF) can be used as a measure of favourability, or lack of favourability, of progression on the arterial, as follows:

$$\text{Average CAF} = \frac{1}{n} \sum_{i=1}^n \text{CAF}_i \quad (6)$$

In the above expression  $\text{CAF}_i$  represents the *Coordination Adjustment Factor* at a particular intersection  $i$ , which is then averaged for  $n$  intersections on a signalized arterial street.

We illustrate the concept using the following example. We consider an arterial segment with variable link lengths and volumes as shown in Fig. 3. There are two-lanes in each direction. The cycle time is 100s at all intersections. We use the Synchro model for calculating average CAF. Three scenarios are considered with progression favourable (i.e. offsets) in the eastbound direction (EB), the westbound direction (WB) and a balanced progression in both directions.

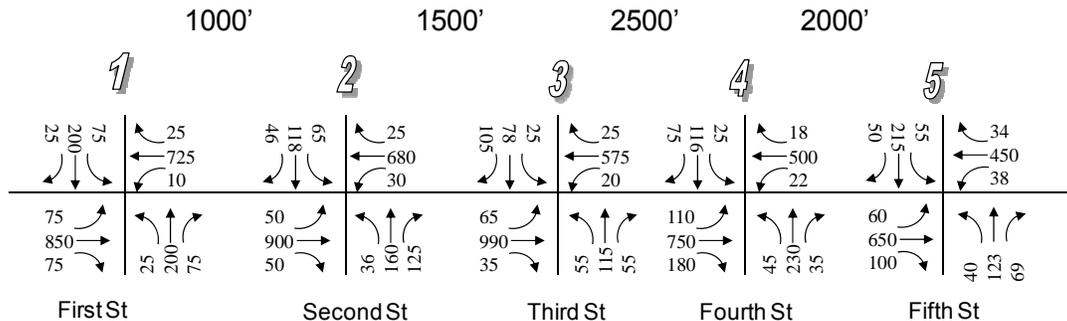


Figure 3 – Scenario for QOP assessment models.

Table 3 shows the average CAF values for EB, WB and two-way progression. The average CAF values for the first intersection in either direction are ignored as the arrivals at the first intersection are considered to be random and not affected by coordination (i.e. CAF=1).

It can be seen from this table, when progression is favourable in the EB direction, the average CAF value for EB (0.32) is less than the average CAF value in the WB

direction (1.27). The favourable progression (offsets) in the EB direction results in lower impedance to the vehicles moving in that direction, hence the lower average CAF values. The average CAF values are reversed in the EB direction (1.25) and in the WB direction (0.44) when we have a favourable progression in the WB direction.

Table 3 – Average CAF Values for EB, WB and Two-Way Progression

	EB Progression		WB Progression		Two-Way Progression	
	CAF EB	CAF WB	CAF EB	CAF WB	CAF EB	CAF WB
Intersection 1	1.00	2.03	1.00	0.31	1.00	1.23
Intersection 2	0.42	0.78	1.72	0.50	0.58	0.41
Intersection 3	0.47	1.75	0.81	0.49	0.40	0.71
Intersection 4	0.18	0.52	1.62	0.44	0.27	0.43
Intersection 5	0.20	1.00	0.85	1.00	0.24	1.00
<b>Average</b>	<b>0.32</b>	<b>1.27</b>	<b>1.25</b>	<b>0.44</b>	<b>0.37</b>	<b>0.69</b>

When a balanced progression scheme is applied to both directions, the average CAF values are relatively low with no direction having a particular advantage. The difference in the values of the average CAF in the EB direction (0.37) and in the WB direction (0.69) is much smaller than in the previous cases, as expected in a two-way progression scheme; however, there are still differences in the values due to uneven network and traffic characteristics (note that the CAF ratio has changed from approx. 1:4 to only 1:2).

The average CAF values can be used as a measure of progression quality on an arterial street, with lower values representing a favourable progression and higher values representing an unfavourable progression. It should be noted, though, that the average CAF values are a measure of progression quality alone and cannot be used as a measure for LOS. In the next section we link the CAF to assess LOS using average delay for the street segments.

### LOS Analysis Using Average Arterial Control Delay (AACD) per Intersection

Intersection control delay has a significant effect on the movement of vehicles on a signalized arterial street and, as such, is a major factor in determining the average travel speed. A lesser delay at the signalized intersection increases the average travel speed and results in an improved LOS. In this section we calculate the average arterial control delay (AACD) per intersection for the entire street, in each direction, using the following formula:

$$Avg\ Arterial\ Control\ Delay\ Per\ Inter\ sec\ tion(AACD) = \frac{\sum_{i=1}^n (CCF)_i \times v_i}{\sum_{i=1}^n v_i} \quad (7)$$

$CCF_i$  in Eq. (7) represents the Cyclic Coordination Function value at a particular approach at intersection  $i$  with approach volume of  $v_i$ . This value is volume-weighted,

aggregated and normalized for all intersections on the street, in a particular direction, to calculate the average arterial control delay (AACD) per intersection. The result of the calculation is in *sec/veh/int* or *spvpi*. We then use this value to determine the LOS for the street by employing the same LOS criteria used for a single signalized intersection (Table 4). The AACD can be calculated for each direction separately, as well as for the entire street (both directions) simultaneously. (Note that the table provides also the transitivity values corresponding to the different levels of service, a concept that is introduced later in Eqn. (9)).

Table 4 – LOS Criteria for Signalized Intersections

LOS	Control Delay per Vehicle (s/veh)	Transitivity (ms <sup>-1</sup> )
A	≤ 10	≥ 100
B	10 - 20	50 - 100
C	20 - 35	29 - 50
D	35 - 55	18 - 29
E	55 - 80	13 - 18
F	> 80	< 13

To illustrate this concept, we use the same scenario described in Fig. 3. We calculate the average control delay per intersection for the entire street in the EB direction, the WB direction and both-ways for a coordination scheme favourable in EB, WB and two-way direction. The results are given in Table 5 below.

Table 5– AACD along Entire Arterial and LOS

	EB Progression		WB Progression		Two-Way Progression	
	AACD ( <i>spvpi</i> )	LOS	AACD ( <i>spvpi</i> )	LOS	AACD ( <i>spvpi</i> )	LOS
EB	7.17	A	27.62	C	8.31	A
WB	25.15	C	8.16	A	13.80	B
Two-Way	14.41	B	19.79	B	10.52	B

As can be seen from the table above, when progression is favourable in EB direction the EB LOS is A while the LOS is C in the opposite direction (WB). The LOS values are reversed when a favourable progression scheme is used in the WB direction. The combined LOS for both directions is B in both cases. When a balanced progression scheme for two-way coordination is applied the LOS is A and B in the EB and WB directions, respectively. This is due to a marked reduction in the AACD value in the un-favoured direction. The LOS stays at B for the street as a whole (two-way) in all cases though the AACD varies from 10.52 *spvpi* to 19.79 *spvpi*. These values are at the two extremes of the range for LOS B (Table 4).

The approach described above is useful when delay is the primary impedance to movement of traffic. It excludes running time on street segments, thus accentuating the operational impacts of the signal control policies. Using the volume weighted delays we are able to estimate a LOS for the arterial as a whole (i.e., in both directions, unlike each direction separately in the HCM), which allows the analyst to

assess the impact of the progression scheme in its totality on an arterial street. A similar kind of analysis is possible with the HCM but would require accurate estimation of the Progression Adjustment Factor (PAF). Studies have shown difficulties in judging the correct Arrival Type by field observations and estimation of the PAF (Eidson and Bullock, 2001). In the absence of information, the HCM suggests using Arrival Type 3 (random arrivals) with PAF=1 which means effects of coordination are ignored.

In the next section we use the average travel speed as the LOS criterion (same as used by the HCM). However, the delay in this procedure is calculated, again, using the appropriate *Cyclic Coordination Function* value at each intersection.

### LOS Analysis Using Average Travel Speed

The average travel speed can be computed by substituting the delay value with a *Cyclic Coordination Function* (CCF) value which represents delay at a particular offset.

$$\text{Average Travel Speed} = \frac{L}{\sum_{i=1}^n (TT_i + CCF_i)} \quad (8)$$

In the above expression,  $L$  is the length of the arterial;  $TT_i$  is the travel time on segment  $i$ ;  $CCF_i$  is the cyclic coordination function value at a particular intersection  $i$  for  $n$  intersections on an arterial street. By using CCF the accuracy improves in estimation of control delay, which is a major determinant for LOS estimation on the arterial street.

To illustrate this approach, we use the same scenario described in Fig. 3. Here the average travel speed is computed using the CCF. The LOS is determined using the average travel speed criterion. The results are shown in Table 6.

Table 6 – LOS Analysis using Average Travel Speed with CCF

	EB Progression		WB Progression		Two-Way Progression	
	ATS (mph)	LOS	ATS (mph)	LOS	ATS (mph)	LOS
EB	19.10	B	14.80	C	18.80	C
WB	15.50	C	19.00	B	17.80	C
Two-Way Avg.	17.30	C	16.9	C	18.3	C

The results show, as expected, a better LOS in the direction with favourable progression. For a two-way progression the LOS remains the same and the average travel speed is comparatively similar in both directions. As control delay is calculated with a greater accuracy, the subsequent average travel speed calculation and LOS determination will be better indicators of the conditions in the field. This eliminates the subjective nature of the PAF determination and removes a major factor in inaccurate determination of LOS for signalized arterial streets.

## THE TRAFFIC PERFORMANCE POTENTIAL

In economic theory, the Production Possibility (or Potential) Frontier represents the locus of points at which an economy is most efficiently producing goods and services. The frontier shows there are limits to production capacity. In order to achieve efficiency, a decision must be made about what combination of goods or services should be produced. In Fig. 4, an example of the *Production Potential Frontier* is illustrated. For a given set of productive resources an economy can only produce a limited amount of guns - if all resources were dedicated to military production, or of butter - if all resources were dedicated to civilian production. These are the extreme points of the *Production Potential Frontier*. In between, there exist a number of points which will result in various combinations of production quantities for the two goods. Point A represents more butter - less guns, Point C more guns - less butter and Point B represents a middle point where balanced quantities of guns and butter can be produced.

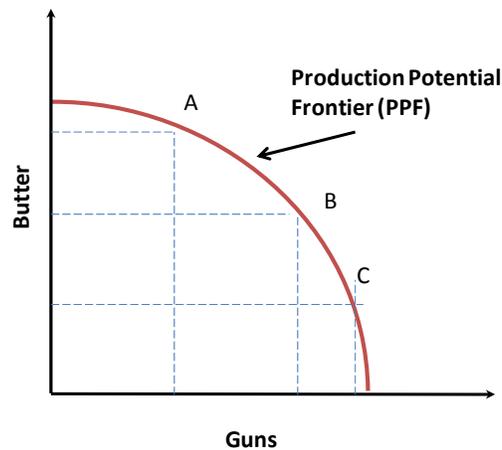


Figure 4 - Production Potential Frontier.

We apply a similar concept to the traffic situation: first, we consider tradeoffs in performance at a single intersection. Then we analyze an entire arterial street.

### Transition Potential Frontier

In the case of an isolated signalized intersection we examine the tradeoffs in performance of the competing traffic streams due to changes in capacity caused by adjustments of the green splits. To explain the tradeoffs for a single intersection we use a new measure of effectiveness (MOE) called *Transitivity* which is defined as follows:

$$\text{Transitivity} = \frac{k}{\text{Average Delay}} \quad (9)$$

*Transitivity* represents the ease with which the signalized intersection can be traversed. Quantitatively it is the inverse of the average delay value. In Equation 9,

when the value of  $k$  is equal to 1000 and the average delay is in seconds, we can express transitivity in milliseconds ( $\text{ms}^{-1}$ ). *Transitivity* has the characteristics of speed if  $k$  assumes a hypothetical unit of distance. It represents the propensity of vehicles to cross the intersection and is a positive measure of performance.

In case of a single intersection, we call the performance potential frontier, the *Transition Potential Frontier* (TPF). The *Transition Potential Frontier* is explained through the following example. We consider the scenario in Fig. 5, an isolated signalized intersection with equal volumes (500 vph) on all approaches. The signal control is a fixed-time controller with two phases for the east-west and the north-south direction. The cycle length is 100s. The g/C split is varied from favourable for the East-West direction to favourable for the North-South direction

The *Transition Potential Frontier* is shown in Fig. 6. For a favourable East-West split, the transitivity is higher in the east-west direction and lower for the North-South direction. When the splits are favourable for the North-South direction, we have higher transitivity in the North-South direction and lower in the East-West direction. For a balanced split the value of the transitivity lies somewhere in between. As the g/C ratio for a particular direction is increased, more capacity is allocated to that direction, resulting in increased transitivity.

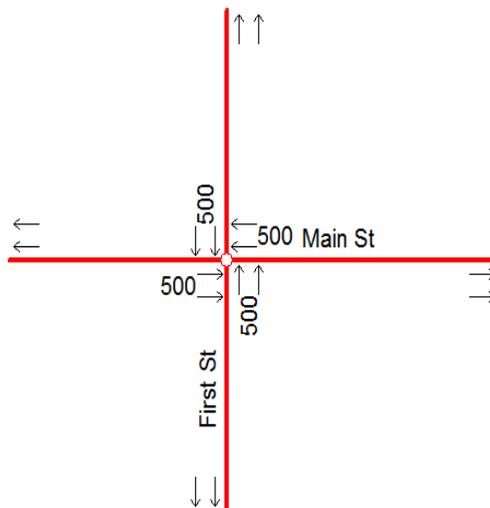


Figure 5 – Scenario for Transition Potential Frontier.

It is straightforward to determine optimal controls for a particular design volume that will maximize transitivity (or minimize delay). But in practice the design volume rarely matches with the actual traffic volume at the intersection. The design volumes are for representative conditions and not the actual traffic volumes at the intersection. A fixed-time signal controller can be adjusted for time of day, still there will be some variation from the design volume. Fig. 6 shows the loss in transitivity (in the East-West direction) if the signal settings are set for a balanced volume but the actual volume at an intersection is higher in the East-West direction.

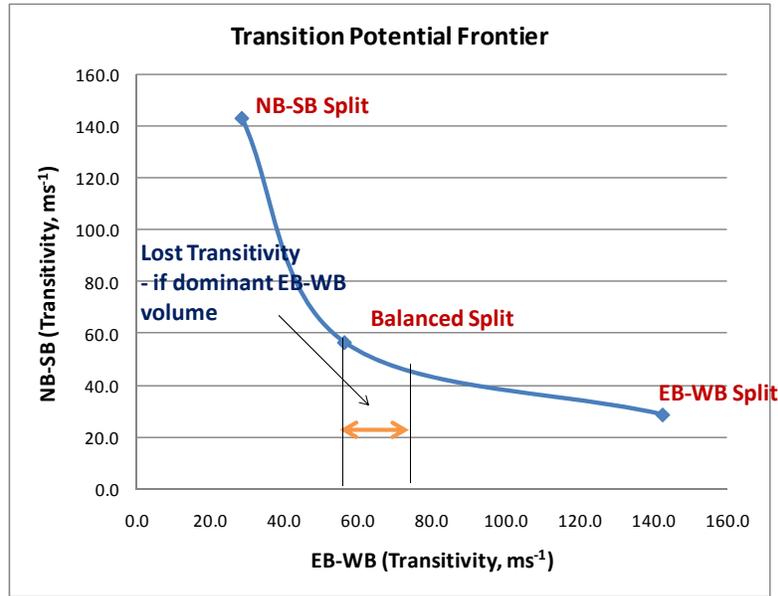


Figure 6 – Transition Potential Frontier with variations in splits.

A similar situation occurs if the signal settings are preset for a volume of 600 vph in the east-west direction and 400 vph in the north-south direction. The optimal split in that case will be a 60/40 split favouring the east-west direction. But if the actual volume is 500 vph in each case, there is a degradation of transitivity in the north-south direction.

Adaptive signal control may be a suitable solution for this kind of problem. However, it may not be practical or affordable to install adaptive control at all signalized intersections but it is definitely desirable to update the signal settings for changing traffic volumes (depending on time of the day, season, day of the week, special events, etc.).

In the next section we apply the performance potential frontier to signalized arterials.

### Progression Potential Frontier

Progression schemes on two-way arterial streets are usually a compromise between the preferences given to the two directions. Common schemes involve: one-way preferential treatments (say, either EB or WB) and two-way “balanced” treatment. Additional options include, for instance, volume-weighted progressions in the two directions (e.g., PASSER II (Chang and Messer, 1991) or MAXBAND (Little et al 1981)) and individual link-weighted progressions using a variety of user specified preferences (e.g., MULTIBAND (Gartner et al, 1990)). In any case, the fact remains that there is sort of a “zero-sum” phenomenon: giving preference to one direction (i.e., improving the LOS for that direction) will invariably result in a degradation of LOS in the other direction. Thus, there is a tradeoff between the performance advantages that either direction can enjoy. This is another manifestation of the fact

that there is a limited resource (street capacity) that has to be shared among competing demands.

We introduce the concept of a *Progression Potential Frontier* in this case. This concept enables one to evaluate clearly the tradeoffs in performance that can result from the preferential treatment of one direction over another. The tradeoff here is the allocation of street capacity that is shared between the two directions. The signal settings for a pre-timed signal are set based on time of day or remain unchanged during extended periods. The volumes for which these signal settings are designed may vary throughout the day. Due to this variation, the street or intersection capacity is not used effectively. Employing the *Performance Potential Frontier* we can see the extent to which variation from optimal conditions occurs. Moreover, by implementing an on-line version of this concept one may be able to continuously adjust controls in order to maintain optimal utilization of the street capacity..

We illustrate the concept of the *Progression Potential Frontier* using a scenario shown in Fig. 7. We consider an arterial segment with variable link lengths and volumes. The cycle time is 100s at all intersections with two-lanes in each direction. The average travel speed is calculated utilizing the *CCF*. Three scenarios are considered with progression favourable (i.e. offsets) for the eastbound direction (EB), the Westbound direction (WB) and balanced progression for both directions. Three different cases are analyzed: one with volumes as shown in Fig. 7 and two additional cases with  $\pm 20\%$  of the indicated volumes.

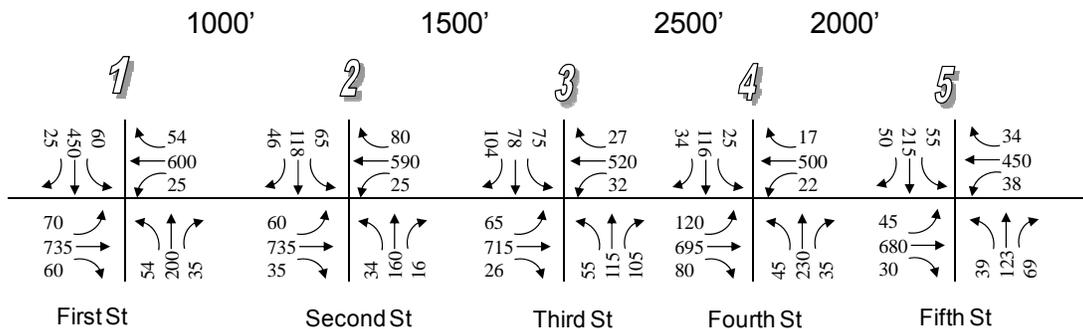


Figure 7 – Scenario for Arterial Progression Potential Frontier Analysis.

In Fig. 8 we plot the average travel speed values for the three cases for the three different progression schemes: favouring EB, WB and two-way. This results in three different curves or so-called “frontiers” for each volume level.

As can be seen in Fig. 8, in general, as the volume-level decreases the average travel speed increases. For a particular volume-level, for the WB progression (WBP) the average travel speed is higher in the WB direction and lower in the EB direction. As the progression scheme changes, the average travel speed also changes. When we have an EB progression (EBP), the average travel speed is now higher for the EB direction. There exists a middle point, where the speeds are approximately similar corresponding to a two-way progression.

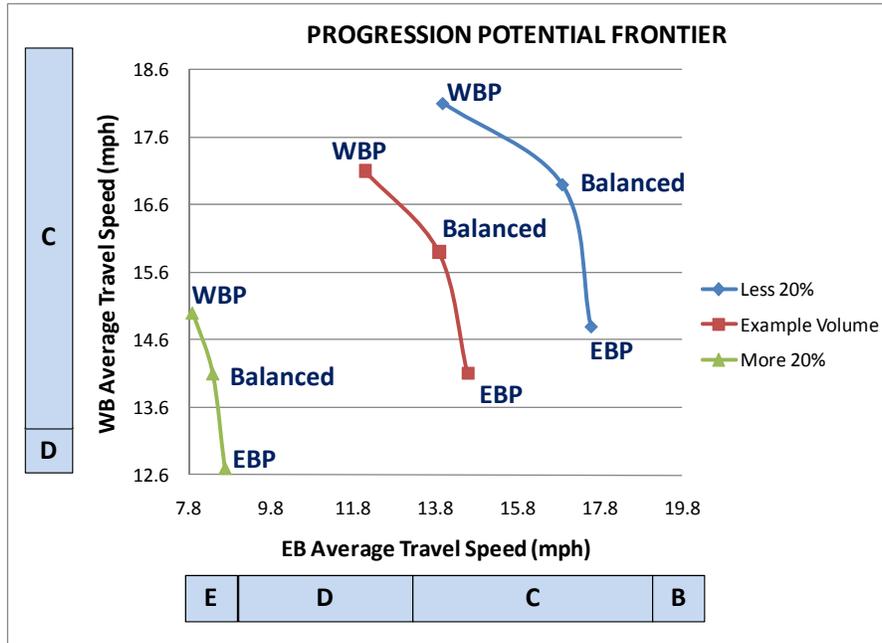


Figure 8 – Progression Potential Frontiers and LOS – three cases.

For a particular case, as we move along the curve, or the “frontier,” (i.e. change the progression scheme), the average travel speed or the LOS improves or degrades (the LOS is shown in adjacent bars). The signal control can be adjusted in a way to favour a particular direction depending on the time of the day and improve the LOS at the cost of those travelling in the reverse direction. In this way, designers can evaluate the tradeoffs in performance that would result from varying degrees of preferences to the two directions. This concept can be applied to individual signalized intersections and extended to more complex network configurations.

## CONCLUSIONS

The most valuable resource in an urban network is the intersection capacity. Traffic signal controls are often the determining factor in the functioning of urban street systems because they enable the effective utilization of this resource. This paper introduces concepts of microeconomics for the analysis and evaluation of signal control policies. These concepts enable one to evaluate clearly the tradeoffs in performance that can result from competing demands for a given set of limited resources. In case of an isolated signalized intersection the tradeoff is between the capacities allocated to the competing traffic streams by the green splits. Traffic control at single intersections involves balancing competing demands of the different traffic streams for limited capacity at the intersection. Similarly, progression schemes on two-way arterial streets involve a compromise between the preferences given to competing directions of traffic flows on the arterial. Again, there is a tradeoff between the performance advantages that each traffic stream can enjoy. This phenomenon is

akin to tradeoffs in production capabilities of economic systems that gives rise to the well-known “Production Potential Frontier”. We introduce a similar concept for signalized intersections and arterials. In the case of an isolated intersection we call it the “Transition Potential Frontier”. In the case of a signalized arterial we call it the “Progression Potential Frontier” (PPF). We also introduce a number of measures to evaluate the performance of signalized intersections and arterials using the Level-of-Service (LOS) concept.

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