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THE EFFECT OF DATA INACCURACY ON THE PERFORMANCE OF TRAFFIC SIGNAL TIMING PLANS

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Abstract

This paper explores the performance of signal timing plans calibrated with perfect or imperfect information. The arrival information considered include arrival rates and arrival distributions. The study is conducted for different levels of arrival rates and different forms of arrival distributions under a wide range of arrival information inaccuracy, traffic intensity, and intersections with balanced and unbalanced flows.

Our results indicate that the increase in delay, the number of stops, and queue length is in general insignificant when the arrival distribution used to calibrate the optimal timing plan is over- or under-estimated. For the same level of over- or under-estimation, the increase in delay and other measures can be high only when the flow level is very high. The effect, however, is attenuated for overestimation of flow since the cycle length is bounded by a predetermined upper bound. Overall, underestimation of flow appears to be more serious than overestimation of flow in terms of increase in total delay.

Keywords: Traffic signal, optimization, traffic control.

Executive Summary

The design of any traffic signal timing plans requires vehicle arrival information from all approaches. Most modern traffic responsive signal timing strategies make use of extensive on-line data, which in turn requires a wide coverage of surveillance systems, to predict vehicle arrivals on the real-time basis. Based on the predicted arrivals in the immediate future, optimization techniques are employed to determine if the current signal setting should be extended or reset. The performance of these strategies, therefore, depends heavily on accuracy in predicting arrivals. There is no general consensus regarding the benefits of these strategies. In this study, we provide some quantitative results to demonstrate when and how the performance of a signal timing plan is sensitive to the accuracy of arrival information used to calibrate the plan.

Our study started with constructing a set of base scenarios in which traffic signal timing plans are optimized with data that contain perfect arrival information. For each scenario, we then developed another timing plan using data with imperfect arrival information. The performance from these two timing plans were compared for light, moderate, and heavy traffic conditions, for a wide range of arrival distributions, and under intersections with balanced or unbalanced flows.

The error range for arrival information considered in this study is between 1% and 15%. Arrival information has two components, arrival rates and arrival distributions. Our results indicate that inaccuracy in arrival distributions contributes little to the increase in delay, the number of stops, and queue length. For prediction errors in flow levels, the increase in delay and other measures is within 4% when flow levels are over- or Underestimated under low or moderate heavy traffic. For the same level of over- or under-estimation, the increase in delay and other measures can be high only when the flow level is very high. The effect of overestimation, however, is less pronounced than the effect of underestimation since the cycle length is bounded by a predetermined upper bound. The highest increase in delay occurs when flow is underestimated in the situation with high flow level.

1. BACKGROUND

The developments of traffic signal control strategies have gone through many stages. For the past three decades or ***so,*** traffic signal timing plans have evolved from ones that are entirely dependent on historical information, often referred to as the fixed timing plan, to the more sophisticated ones that combine historical information with real-time traffic information.

Traffic signal control strategies developed in different stages have often been categorized into three generations. The first generation control strategy uses fixed timing plans that are generated off-line using historical flow data. To develop these plans, traffic patterns at an intersection, including traffic arrivals, turning movements, and saturation flows are measured on all approaches during different time periods of a day. The plans are then optimized off-line for the given data using recipe from an engineering handbooks like the Highway Capacity Manual. Upon implementation, alternative pre-developed control plans are selected based on time of day or on average flow conditions.

The **1.5** generation control strategy generates automatically signal timing plans based on TRANSYT-7F, MAXBAND, or other computer optimization programs. Data used to calibrate these programs are usually collected on-line. **A** new timing plan is generated at fixed time intervals and compared the one currently in operation. The new timing plan will be implemented if its projected performance is superior to the old one. The implementation of a new timing plan is either manually controlled or based on the average flow condition.

The second generation control strategy computes and implements signal timing plans on-line based on surveillance data. It also utilizes a prediction model to predict near-term changes in traffic demand. The predicted data combined with historical data are used to provide estimates of volume and speed, and to generate optimal timing plans. Though the optimization process is repeated at 5-minute intervals, the new timing plans generated cannot be implemented more often than every **10** minutes to avoid potential transition disturbances. Traffic data are collected by detectors located at the stop lines and mid-points of all links.

The third generation control strategy distinguishes itself from the previous ones in that it is a fully traffic responsive on-line traffic control system. For signal timing plans of this generation, there are no predetermined parameters. Cycle length, offsets, and split are all determined on-line with optimization models. Prediction of the traffic flow is often made for a very short period of time. The cycle length, splits and offsets are then adjusted on-line in response to the time-varying traffic demand to reduce the total delay based on the predicted arrivals. Also, smoothed values, averaged over the most recent control periods, instead **of** historical data are used in updating and implementing the optimal signal control plan. Some typical systems of this generation include SCOOT, OPAC, PRODYN, and SCATS.

Though the procedures to develop signal timing plans under different generations may differ in detail, they all share some similar processes. There are two principal components common to the development of all signal timing plans. The first component is a collection process which estimates or predicts vehicle arrival levels. The second component is an optimization process which applies various optimization techniques to obtain optimal cycle length, offset, and split based on the data acquired in the data collection process.

If one views all these signal control strategies from the perspective of data collection, one may classify various strategies into two categories, those that are based on the off-line data and those that are based on the on-line data. The signal control strategies based on the off-line data, such as the ones in the first generation, require estimation of time-of-day arrival rates from the available historical data, an approach that is intended to capture long term flow average. ***On*** the other hand, the control strategies based on the on-line data, such **as** those from the second or third generations, emphasize more and more on the short term prediction of traffic flow and become increasingly costly because they usually rely heavily on more advanced communication device, shorter data sampling intervals, and additional maintenance service. It should be noted that estimation or prediction is always subject to errors in one form or another. In addition, the behavior of city street traffic is highly unpredictable and the noise level is usually much higher than freeway traffic. Even with very sophisticated surveillance systems, there is a limitation to one's prediction. Consequently, the predicted arrivals within a certain time interval could always deviate from the actual ones to various degrees. It is difficult to include factors such as parked vehicles, vehicles entering or exiting a parking lot, pedestrians, and others, into one's prediction.

From the perspective of the optimization process, it is likewise difficult to obtain ***the optimal*** solution at a reasonable computational effort. Existing optimization models for developing traffic signal control strategies are either a set of approximations and bounds (e.g. feedback control) or exact formulations (e.g. mixed integer programming ones) with solutions only obtainable with numerical approximations. The parameters for signal timing plans, such as cycle length, offset, and split, may only lead to near optimal solutions[1]. The choice of an appropriate objective function is another complicated issue. In terms of the total delay, the total waiting time of ten people with each waiting for one minute is equal to the waiting time of a single person for ten minutes. When it comes to the societal acceptability, these two delays will have complete different meanings. Different objective functions, such as the minimization of the maximum queue length, the minimization of the total delay, and the minimization of the total number of stops, may not yield the same set of design parameters.

Both of these two factors may render a specific timing plan developed to achieve some form of optimization only a suboptimal one. Fortunately, the suboptimal signal timing plan may not be significantly inferior to the optimal one. The comparison between the performance of less sophisticated signal timing plans (e.g., such as time-ofday plans) and the more advanced ones (e.g. full traffic responsive timing plans) was made by a number of studies in the past. The results from an early study by Kreer (1976) suggest that the gain under a traffic responsive system over a well designed time-of-day traffic signal system is very minimal. Tests conducted by TRRL even concludes that fixed-time control is more effective than responsive ones (Holroyd and Robertson, 1973). The most recent criticism of traffic responsive strategies using the rolling horizon scheme appears in a paper by Newell (1996) in which it shows that the rolling horizon scheme has some undesirable features that would lead to higher delays in a long run.

For this study, we do not attempt to assess the performance of numerous signal timing control strategies developed thus far. Rather, we intend to explore the level of improvement one can achieve if one is able to acquire very accurate arrival information to calibrate traffic signal timing plans. An equivalent question would be: How the performance of a signal timing plan will degrade if the data used to calibrate it are subject to inaccuracy? We will address this question by performing sensitivity analysis with various flow characteristics and prediction errors.

The remainder of the report is organized into four sections. Sec. 2 discusses our study approach. The base scenarios, assumptions, and the choice of the delay formula used in our study will be

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[1] This will be discussed further later.

given. Sec. **3** presents the results of the sensitivity analysis. We show with a total of eighteen scenarios how performance of a signal timing plan changes if the input data are subject to various level of inaccuracy. This is performed under a wide range of flow intensity, arrival distributions, and data inaccuracy levels. Our observations and findings from the results are given in Sec. **4.** Sec. 5 presents our conclusions and recommendations.

2. STUDY APPROACH

In order to make the result transparent for analysis, we consider an isolated intersection instead of an arterial or a network. Furthermore, we assume that the single intersection has no left or right **turns.** We evaluate the performance of an optimized signal timing plan calibrated for such an intersection in the situation when arrival information used to calibrate the signal timing plan is imperfect. There are two components associated with arrival information, arrival rates and arrival probability distributions. In reality, arrival rates often vary with time of day, whereas arrival distributions vary spatially from intersection to intersection. Therefore, we choose to perform sensitivity analysis based on all levels of arrivals and a wide range of vehicle arrival distributions.

In this section, we will construct a set of base scenarios with different arrival characteristics. In each scenario, a unique optimal signal timing plan is generated with perfect information about the arrival characteristics, such as the arrival rate and the arrival distribution. The scenarios created cover light, moderate, and heavy traffic conditions, and a wide range of arrival distributions, represented by variance-to-mean **(v/m)** ratios. The measures of performance obtained with the base scenarios are used for comparing the performance of signal timing plans developed with imperfect information, such as under- or over-estimation of vehicle arrivals and misrepresentation of arrival distributions.

The objective function used to develop the signal timing plan is the minimization of total delay. Total delay is also used as a measure of performance for evaluating the signal timing plan. However, other measures of performance, such as the resulting queue length and the total number of stops are also compared under the two plans.

2.1 The selection of delay formula

There are a number of formulas developed in the past to estimate vehicle delay at a signalized intersection. The formulas considered in this study are the ones developed by Webster **(1958),** Miller **(1968),** and Newell **(1965).** This section discusses these three formulas, their underlying assumptions and limitations, and our choice of formula in obtaining optimal cycle length and split. The following is a set of notation used throughout the section:

c = cycle length (sec);
4 = average number of arrivals per unit time (veh/sec);
g = effective green time (sec);
$\lambda = g/c$ = proportion of cycle that is effectively green;
I = sum of variance-to-mean ratios for the arrival and departure processes per cycle;
$x = qc/(sg)$ = flow intensity = ratio of average number of arrivals per cycle to maximum number of departures per cycle;
s = saturation **flow** (veh/sec)
$E[Q]$ = expected queue length at the beginning of red phases;

Among these variables, q and I are related to the characteristics of arrivals, s is related to the roadway configuration. These are non-decision variables which are assumed to be directly measurable in the field. g and c are decision variables which are obtained based on characteristics of vehicle arrivals and geometry of the intersection in the optimization process.

Webster's formula

Webster's delay formula is:

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{E[Q]}{q} - 0.65(\frac{c}{q^2})^{1/3} x^{(2+5\lambda)}$$

where

$$E[Q] = \frac{x^2}{2(1-x)}$$

Webster's delay formula assumes Poisson arrivals and deterministic departures. Thus the variance-to-mean ratio is always 1. There are three terms in the formula. The first term is the average delay when the arrivals are regular. The second term represents the additional delay caused by the randomness in arrivals. The third term is an empirical correction term. The expected queue length, **E[Q],** in the second term is derived using queuing theory for Poisson arrivals and constant service times. It is further assumed that Q is always positive. The second term generally overestimates the stochastic delay because it does not account for the situations when the queue clears itself before the signal turns red. Therefore, a third term is used to correct this error. This correction term is obtained through fitting empirical calculation of delays. The application of this equation is limited because of its assumptions.

Miller's formula

Miller's delay formula is in the form:

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{(1-\lambda)}{2(1-\lambda x)}\{\frac{2E[Q]}{q}\}$$

where

$$E[Q] \approx \frac{\exp\{-1.33\sqrt{sg}\,(1-x)/x\}}{2(1-x)}$$

Miller relaxed the restriction of Poisson arrivals to a generalized stationary point process with independent increments. However, regular departure patterns were still assumed. He then derived the expression for average delay in equilibrium conditions. A method due to Bailey (1954) for bulk-service queues was used to calculate **E[Q].** The exact formula involves finding imaginary roots. Therefore, Miller used the above expression to approximate the exact value for the range of flow intensity between 0.4 and **0.96.** Although this formula can be used for general arrivals, the assumption of regular departures is still somewhat restrictive.

Newell's formula

Newell's delay formula is given by:

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{E[Q]H(\mu)}{q}$$

where

$$E[Q] \approx \frac{I}{2(1-x)}$$

$$H(\mu) = \exp[-\mu - \frac{\mu^2}{2}]$$

$$\mu = (1-x)(\frac{sg}{Z})^{0.5}$$

Recognizing the limitation of Webster's formula due to its assumptions, Newell relaxed the assumptions on both arrival and departure processes. His formula also contains a deterministic and a stochastic component. The deterministic component is exactly the same as Webster's, however, the second terms is not. The variability in arrivals and departures are now captured by the variance-to-mean ratio, ***I*****,** which can be obtained directly from field observations. The residual queue length at the end of each green phase does not have to be positive all the time. In other words, queue can be cleared during some cycles. He then derived the expression for **E[Q]** under these conditions. Because this expression overestimates **E[Q]** when x is less than 0.7, a correction factor, H(μ), is applied. Since Newell's delay formula has least restrictions for the arrival and the departure process, it can be applied to most situations.

Our selection of a formula

All three formulas contain two parts, a deterministic component and a stochastic component. The deterministic components in all of them are identical, whereas the stochastic components are different due to assumptions and formulation approaches. The residual queue lengths at the beginning of a red phase are treated in different ways in these formulas.

Of the three formulas, we choose to adopt Newell's formula in our study for obtaining the optimal cycle length and split, and computing the relevant measures of performance. Our decision is made based on the following rationale:

- Newell's formula is the most general one and can be applied to most situations. There is no implicit assumption regarding the underlying arrival and departure processes. Arrival and departure distributions are represented by variance-to-mean ratios which are decision variables in the formula. Both of these ratios can be measured in the field.

- Newell's formula is more accurate than others. A number of previous simulation studies and field observations on comparing several delay and queue length formulas also indicate that Newell's formula gives the most accurate results (Cronje, 1983, Tarko, 1994).

2.2 Use of variance-to-mean ratios

In many previous analytical studies, Poisson arrivals were always assumed. In reality, Poisson distribution is probably valid only under very limited conditions. Though there are a number of empirical arrival distributions developed in the past based on the headway and discharge flows measured in the field, such as the one proposed by Koshi (1982), whether these distributions can be applied to general intersections has not been confirmed. In fact, according to Newell, "the true distribution is difficult to predict from any theory **of** driver behavior" (Newell, 1989). We, instead, use variance-to-mean **(v/m)** ratios to represent a wide range of arrival distributions. For Poisson arrivals, the v/m ratio is exactly 1.

Variance-to-mean ratio has two components, one for the arrival process and the other for the departure process. According to Newell (1989), a typical ratio for the arrival process varies between 1 and 2 for a regular intersection under normal traffic arrivals. **A** typical ratio for the departure process varies between **1/4** and 1/2. Therefore, our sensitivity analysis will be based on the v/m ratio of these ranges. The v/m ratio for any specific intersection can always be measured in the field.

2.3 Base scenarios

There are a total of eighteen base scenarios. These scenarios are further divided into two groups with nine scenarios in each group. The first group assumes that flows from all approaches are similar, typical for a critical intersection. The second group assumes that flows from all approaches are unbalanced, representing an intersection of a main and a minor street. Within each group we consider three different flow levels (light, medium, and high) and three different variance-to-mean ratios (light, medium, and high). A scenario in a group is a combination of a unique flow level and a unique variance-to-mean ratio. For example, a typical scenario could be one with a low level of flow (e.g. 200 vehicles per hour per lane) and a medium level of variance-to-mean ratio (e.g. v/m = 1.4). For every scenario, an optimal traffic signal timing plan is calibrated for the given parameters.

Tables 1 and 2 outline the flow levels and v/m ratios used in our study for the scenarios in group 1 and group 2, respectively. For each scenario, the optimal cycle length and green phase for the major approach are also shown in the table along with measures of performance, such as the total delay per second, the total number of stops per second, and queue length.

The flow rates representing low, medium, and high levels of traffic in the first group are taken from typical 24-hour weekday flow patterns observed at sites in Toronto, Canada (McShane and Crowley, 1976). However, the high flow levels are reduced from 900 to 756 vehicles per hour per lane to ensure that an overestimation of traffic intensity will not lead to an over saturation case. For the scenarios in group two, the total flow level from all approaches in each scenario is the same as its counterpart in group 1, except it is partitioned unevenly among the major and minor streets. We assume here that the flow rate from the major street is three times higher than that from the minor street.

Table 1. Scenarios for Critical Intersections

	Flow (vphpl)		V/M Ratio		Optimal	Arterial	Total	# of	Queue
Scenario	Major	Minor	Major	Minor	Cycle	Green	Delay	stops	Length
1	756	756	2.5	2.5	160	75	40.4	0.38	24.1
2	756	756	1.875	1.875	146	68	34.2	0.39	19.1
3	756	756	1.25	1.25	130	60	27.5	0.39	13.8
4	600	600	2.5	2.5	85	37.5	17.7	0.29	10.9
5	600	600	1.875	1.875	78	34	14.9	0.29	8.5
6	600	600	1.25	1.25	70	30	11.9	0.29	6.1
7	108	108	2.5	2.5	58	24	3.56	0.04	2.9
8	108	108	1.875	1.875	52	21	2.8	0.04	2.2
9	108	108	1.25	1.25	44	17	2.0	0.04	1.5

Table 2. Scenarios for Intersections of a Major and a Minor Street

	Flow (vphpl)		VIM Ratio		Optimal	Arterial	Total	# of	Queue
Scenario	Major	Minor	Major	Minor	Cycle	Green	Delay	Stops	Length
10	1134	378	2.5	1.25	158	111	30.3	0.35	18.1
11	1134	378	1.875	1.25	149	105	27.2	0.36	15.7
12	1134	378	1.25	1.25	139	96	24.1	0.36	13.2
13	900	300	2.5	1.25	82	54	12.6	0.25	7.8
14	900	300	1.875	1.25	77	50	11.3	0.25	6.7
15	900	300	1.25	1.25	71	46	10.0	0.26	5.6
16	162	54	2.5	1.25	58	36	2.7	0.03	2.2
17	162	54	1.875	1.25	53	32	2.3	0.03	1.8
18	162	54	1.25	1.25	48	28	1.9	0.03	1.5

The mean-to-variance ratio used is the sum of the v/m ratios for arrivals and departures. It has been shown by Van As (1991) that departure v/m ratio is an increasing function of arrival v/m ratio. Therefore, the high level of variance-to-mean ratio is set to be 2+0.5=2.5 and the low level is set to be 1+0.25=1.25. While the medium level is set to be the midpoint between high and low levels which is 1.875. In group 1, the flow levels and variance-to-mean ratios are assumed to be the same for both major and minor approaches. In group 2, the variance-to-mean ratio for the main approach varies and those for the minor approach remains constant.

For the intersection considered in our study, the four approaches have the same geometry with saturation flow at 1,800 vehicles per hour per lane. The lost time is assumed to be 10 seconds in all scenarios. The upper bound for the green phase is set at 3 minutes, and the lower bound at 15 seconds.

3. SENSITIVITY ANALYSIS

The sensitivity analysis is performed for all eighteen scenarios, summarized in Tables 3 to 24.

For each scenario, we first obtain an optimal signal timing plan using the vehicle arrival rate and the v/m ratio given in the base scenario, shown in columns *6* and 7 of Tables **1** and 2. We assume here that the arrival information in the base scenario is accurate and the plan thus is the optimal one. In our sensitivity analysis, we assume that the arrival rates or V/M ratio are either over or under estimated, within the range of less than 15% of prediction error, and recalculate the signal timing plan with imperfect arrival information. The signal timing plan calculated this way should be only suboptimal. It should be noted that the choice of this error range is subjective. It is, however, a range that is normally attainable with regular data collection techniques. The differences of the total delay resulting from the optimal and the suboptimal plans are then compared. Tables **3** to 24 show the percentage of increase or decrease (indicated by the negative number) in queue length, number of stops and total delay for each scenario resulting from suboptimal plans.

Taking Table 5 as an example. The table entry for scenario 8 and 11% of over-estimation of V/M ratio is 0.5. This means that the delay resulting from a signal timing plan using V/M ratio which is overestimated by 11% is 0.5% higher than the delay resulting from a timing plan calculated with unbiased data.

Table 3. % of Increase in Total Delay (Over-estimation of **Flow**)

								Level of Over-estimation							
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	0.2	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
2	0.2	0.8	1.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
3	0.2	0.9	2.1	3.7	5.9	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
4	0.1	0.2	0.3	0.5	0.7	0.9	1.2	1.6	1.9	2.4	2.9	3.4	4.1	4.8	5.5
5	0.1	0.2	0.3	0.5	0.8	1.0	1.4	1.8	2.2	2.7	3.3	3.9	4.6	5.4	6.2
6	0.1	0.2	0.4	0.6	0.9	1.2	1.6	2.1	2.6	3.2	3.8	4.6	5.4	6.3	7.3
7	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.3
8	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.4
9	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.4	-0.4

Table 4. % of Increase in Total Delay (Under-estimation **of** Flow)

								Level of Under-estimation							
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	0.1	0.5	1.1	2.0	3.1	4.4	6.1	7.9	10.1	12.5	15.2	18.3	21.8	25.6	29.9
2	0.1	0.6	1.3	2.4	3.7	5.4	7.4	9.8	12.5	15.7	19.4	23.6	28.4	34.0	40.4
3	0.2	0.7	1.7	3.0	4.9	7.1	10.0	13.4	17.5	22.4	28.3	35.5	44.1	54.8	68.1
4	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.7	0.8	1.1	1.3	1.5	1.8	2.1
5	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.6	0.8	1.1	1.3	1.6	1.9	2.2	2.6
6	0.0	0.0	0.0	0.1	0.3	0.4	0.6	0.9	1.2	1.5	1.8	2.2	2.6	3.1	3.6
7	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.5
8	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5
9	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5

Table 5 % of Increase in Total Delay (Over-estimation **of** V/M Ratio)

								Level of Over-estimation							
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
4	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
5	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
6	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
7	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.6
8	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.6
9	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7

Table 6 % **of** Increase in Total Delay (Under-estimation of V/M Ratio)

								Level of Under-estimation							
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.4	-0.5	-0.5	-0.5	-0.6
8	0.0	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4	-0.5	-0.5	-0.6	-0.6	-0.6
9	0.0	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.5	-0.5	-0.6	-0.6	-0.7	-0.7

Table 7 % of Increase in Total Delay (Over-estimation of Flow)

							Level of Over-estimation								
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
10	0.4	1.1	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
11	0.7	1.8	3.2	5.0	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
12	1.2	2.7	4.6	6.9	9.6	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
13	0.1	0.2	0.4	0.6	0.9	1.2	1.6	2.0	2.5	3.0	3.5	4.1	4.8	5.5	6.3
14	0.2	0.4	0.7	1.1	1.5	1.9	2.4	2.9	3.5	4.2	4.9	5.6	6.4	7.3	8.2
15	0.4	0.8	1.2	1.7	2.3	2.9	3.6	4.3	5.0	5.9	6.8	7.7	8.7	9.8	10.9
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2

Table 8 % of Increase in Total Delay (Under-estimation of Flow)

							Level of Under-estimation								
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
10	0.0	0.3	1.0	2.1	3.6	5.8	8.5	12.0	16.5	22.2	29.6	39.2	52.1	70.1	96.6
11	-0.3	-0.3	0.1	1.0	2.3	4.2	6.8	10.3	14.8	20.8	28.8	39.7	55.1	78.2	115
12	-0.8	-1.2	-1.2	-0.7	0.3	1.8	4.2	7.5	12.1	18.5	27.7	41.1	62.3	99.5	179
13	0.0	0.0	0.0	0.1	0.3	0.5	0.8	1.1	1.5	2.0	2.5	3.1	3.8	4.5	5.3
14	-0.1	-0.2	-0.3	-0.3	-0.2	-0.1	0.1	0.3	0.6	0.9	1.4	1.8	2.4	3.1	3.8
15	-0.3	-0.6	-0.8	-0.9	-1.0	-1.1	-1.0	-1.0	-0.8	-0.6	-0.4	0.0	0.4	0.9	1.5
16	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4
17	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2

Table 9. % of Increase in Total Delay (Over-estimation of V/M Ratio)

							Level of Over-estimation								
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4
17	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4
18	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3

Table 10. % of Increase in Total Delay (Under-estimation of V/M Ratio)

							Level of Under-estimation								
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
11	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
12	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
16	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.4	-0.4
17	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4
18	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.4

Table 11. % **of** Increase in # **of** Stop (Over-estimation of **Flow)**

	Level of Over-estimation														
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	-0.3	-0.6	-07	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7
2	-0.3	-0.6	-1.0	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2
3	-1.9	-0.7	-1.1	-1.4	-1.8	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9
4	-0.2	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4	-1.6	-1.8	-2.0	-2.2	-2.4	-2.6	-2.8	-3.0
5	-0.2	-0.4	-0.6	-0.8	-1.1	-1.3	-1.5	-1.7	-1.9	-2.2	-2.4	-2.6	-2.8	-3.1	-3.3
6	-0.2	-0.5	-0.7	-0.9	-1.2	-1.4	-1.7	-1.9	-2.2	-2.4	-2.7	-2.9	-3.2	-3.4	-3.7
7	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
8	0.0	0.1	**0.1**	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.6
9	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6

Table 12. % **of** Increase in # of Stops (Under-estimation of **Flow)**

	Level of Under-estimation														
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	0.3	0.6	0.9	1.2	1.4	1.7	2.0	2.3	2.5	2.8	3.1	3.4	3.6	3.9	4.1
2	0.3	0.6	0.9	1.3	1.6	1.9	2.2	2.5	2.8	3.1	3.4	3.7	3.9	4.2	4.5
3	**0.4**	0.7	1.1	1.4	1.7	2.1	2.4	2.8	3.1	3.4	3.8	4.1	4.4	4.7	5.1
4	0.2	0.4	0.6	0.7	0.9	1.1	1.3	1.5	1.6	1.8	2.0	2.2	2.3	2.5	2.7
5	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.5	2.7	2.9
6	0.2	0.5	0.7	0.9	1.1	1.4	1.6	1.8	2.0	2.2	2.5	2.7	2.9	3.1	3.3
7	0.0	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.4	**-0.4**	-0.5	-0.5	-0.6	-0.6	-0.7
8	0.0	-0.1	**-0.1**	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.4	-0.5	-0.5	-0.6	-0.6	-0.7
9	0.0	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.5	-0.5	-0.6	-0.6	-0.7	-0.7

Table **13.** % of Increase in # of Stops (Over-estimation of V/M Ratio)

	Level of Over-estimation														
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	0.0	0.0	-0.1	-0.1	**-0.1**	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
2	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3
3	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3
4	0.0	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	**-0.4**	-0.4	-0.4	-0.5
5	0.0	-0.1	**-0.1**	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4	-0.4	-0.4	-0.5
6	0.0	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4	-0.4	***-0.5***	-0.5
7	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4	-0.5	-0.5	-0.6	-0.6	-0.7	-0.7	-0.8	-0.8
8	-0.1	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4	-0.5	-0.5	-0.6	-0.7	-0.7	-0.8	-0.8	-0.9
9	-0.1	-0.1	-0.2	-0.3	-0.3	-0.4	-0.5	-0.5	-0.6	-0.6	-0.7	-0.8	-0.8	-0.9	-0.9

Table 1 . % of Increase in # **of** Stops (Under-estimation of V/M Ratio)

	Level of Under-estimation														
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
1	***0.0***	***0.0***	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
2	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
3	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
4	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
5	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.6
6	0.0	0.1	0.1	0.1	0.2	0.2	0.3	**0.3**	**0.3**	0.4	0.4	0.4	0.5	0.5	0.6
7	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0
8	0.1	**0.1**	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1
9	0.1	0.1	0.2	0.3	**0.4**	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.1

Table 15. % of Increase in # **of** Stop (Over-estimation of **Flow**)

						Level of Over-estimation									
Scenario	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**	**11%**	**12%**	**13%**	**14%**	**15%**
10	-0.8	-1.6	-2.4	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5
11	-0.8	-1.7	-2.5	-3.3	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5
12	-0.9	-1.7	-2.6	-3.4	-4.3	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1
13	-0.5	-1.1	-1.6	-2.2	-2.7	-3.2	-3.7	-4.3	-4.8	-5.3	-5.8	-6.4	-6.9	-7.4	-7.9
14	-0.5	-1.1	-1.6	-2.2	-2.7	-3.3	-3.8	-4.3	-4.9	-5.4	-5.9	-6.5	-7.0	-7.5	-8.0
15	-0.6	-1.1	-1.7	-2.2	-2.8	-3.3	-3.9	-4.4	-5.0	-5.5	-6.1	-6.6	-7.1	-7.7	-8.2
16	-0.2	-0.3	-0.5	-0.6	-0.8	-1.0	-1.1	-1.3	-1.4	-1.6	-1.7	-1.9	-2.0	-2.1	-2.3
17	-0.2	-0.3	-0.5	-0.6	-0.8	-0.9	-1.1	-1.2	-1.3	-1.5	-1.6	-1.8	-1.9	-2.0	-2.2
18	-0.1	-0.3	-0.4	-0.6	-0.7	-0.8	-1.0	-1.1	-1.2	-1.4	-1.5	-1.6	-1.7	-1.9	-2.0

Table 1 **i.** % of Increase in # **of** Stops (Under-estimation of **How**)

						Level of Under-estimation									
Scenario	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**	**11%**	**12%**	**13%**	**14%**	**15%**
10	0.8	1.6	2.5	3.3	4.1	4.9	5.8	6.6	7.4	8.3	9.1	10.0	10.8	11.7	12.6
11	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5	9.3	10.2	11.1	11.9	12.8
12	0.9	1.7	2.6	3.5	4.3	5.2	6.1	7.0	7.8	8.7	9.6	10.5	11.4	12.3	13.2
13	0.5	1.1	1.6	2.2	2.7	3.3	3.9	4.4	5.0	5.5	6.1	6.7	7.3	7.8	8.4
14	0.6	1.1	1.7	2.2	2.8	3.3	3.9	4.5	5.0	5.6	6.2	6.7	7.3	7.9	8.5
15	0.6	1.1	1.7	2.2	2.8	3.4	4.0	4.5	5.1	5.7	6.3	6.8	7.4	8.0	8.6
16	0.2	0.3	0.5	0.7	0.9	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8
17	0.2	0.3	0.5	0.6	0.8	1.0	1.2	1.3	1.5	1.7	1.9	2.1	2.2	2.4	2.6
18	0.1	0.3	0.4	0.6	0.8	0.9	1.1	1.2	1.4	1.6	1.7	1.9	2.1	2.2	2.4

Table 1 . % **of** Increase in # of Stops (Over-estimation of V/M Ratio)

						Level of Over-estimation									
Scenario	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**	**11%**	**12%**	**13%**	**14%**	**15%**
10	*0.0*	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.4
11	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.3
12	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3
13	0.0	-0.1	-0.1	-0.2	-0.2	**-0.3**	**-0.3**	-0.3	-0.4	-0.4	-0.5	-0.5	-0.5	-0.6	-0.6
14	0.0	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4	-0.5	-0.5	-0.5	-0.6	-0.6
15	0.0	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.4	-0.5	-0.5	-0.5	-0.6
16	-0.1	-0.1	-0.2	-0.3	-0.3	-0.4	-0.4	*-0.5*	-0.6	-0.6	-0.7	-0.7	-0.8	-0.9	-0.9
17	-0.1	-0.1	-0.2	-0.3	-0.3	-0.4	-0.4	-0.5	-0.6	-0.6	-0.7	-0.7	-0.8	-0.8	-0.9
18	-0.1	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4	-0.5	-0.5	-0.6	-0.7	-0.7	-0.8	-0.8	-0.9

Table 1 . % of Increase in # of Stops (Under-estimation of V/M Ratio)

						Level of Under-estimation									
Scenario	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**	**11%**	**12%**	**13%**	**14%**	**15%**
	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4
	0.0	0.1	0.1	0.1	0.1	0.2	**0.2**	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4
	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	**0.3**	0.3	0.3	0.4
	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7
	0.0	0.1	0.1	0.2	**0.2**	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.7
15	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.6
	0.1	0.1	0.2	0.3	**0.3**	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1
	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1
18	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.0

Table **19.** Increase in Queue Length (Over-estimation of **Flow)**

	Level of Over-estimation														
Scenario	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**	**11%**	**12%**	**13%**	**14%**	**15%**
1	-0.7	-1.3	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5	-1.5
2	-0.6	-1.2	-1.7	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1
3	-2.5	-1.1	-1.5	-2.0	-2.4	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5
4	-0.1	-0.2	-0.3	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8	-0.8	-0.9	-1.0	-1.1	-1.1	-1.2
5	-0.1	-0.2	-0.2	-0.3	-0.4	-0.5	-0.5	-0.6	-0.7	-0.8	-0.8	-0.9	-1.0	-1.0	-1.1
6	-0.1	-0.1	-0.2	-0.3	-0.3	-0.4	-0.5	-0.5	-0.6	-0.7	-0.7	-0.8	-0.8	-0.9	-0.9
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 20. Increase in Queue Length (Under-estimation of **Flow)**

	Level of Under-estimation														
Scenario	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**	**11%**	**12%**	**13%**	**14%**	**15%**
1	0.7	1.5	2.3	3.1	4.0	5.0	6.1	7.2	8.4	9.7	11.1	12.6	14.2	16.0	18.0
2	0.7	1.4	2.1	3.0	3.8	4.8	5.9	7.0	8.2	9.6	11.1	12.8	14.7	16.8	19.2
3	0.6	1.3	2.0	2.8	3.7	4.6	5.7	7.0	8.4	10.0	11.9	14.1	16.6	19.8	23.6
4	0.1	0.2	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
5	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
6	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table **21.** Increase in Queue Length (Over-estimation of V/M Ratio)

	Level of Over-estimation														
Scenario	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**	**11%**	**12%**	**13%**	**14%**	**15%**
1	0.0	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.4	-0.5	-0.5	-0.5	-0.6
2	0.0	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4	-0.4	-0.5	-0.5
3	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.4	-0.4	-0.4
4	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	**-0.2**	-0.2	-0.2	-0.2	-0.2
5	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2
6	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 22. Increase in Queue Length (Under-estimation of V/M Ratio)

	Level of Under-estimation														
Scenario	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**9%**	**10%**	**11%**	**12%**	**13%**	**14%**	**15%**
1	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7
2	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.6	0.6
3	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5
4	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3
5	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
6	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 23. Increase in Queue Length Over-estimation of Flow)

	Level of Over-estimation														
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
10	-0.2	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
11	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
12	0.0	0.0	0.1	0.2	0.4	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
13	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2
15	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 24. Increase in Queue Length (Under-estimation of Flow)

	Level of Under-estimation														
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
10	0.3	0.7	1.2	1.8	2.5	3.4	4.4	5.7	7.2	9.1	11.5	14.5	18.6	24.2	32.3
11	0.2	0.5	0.9	1.4	1.9	2.7	3.6	4.7	6.1	7.9	10.2	13.3	17.6	24.0	34.4
12	0.1	0.3	0.5	0.8	1.3	1.8	2.6	3.5	4.8	6.5	8.8	12.2	17.4	26.5	45.8
13	0.0	0.1	0.1	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	1.0
14	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.8
15	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 25. Increase in Queue Length (Over-estimation of V/M Ratio)

	Level of Over-estimation														
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
10	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3
11	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3
12	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
13	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 26. Increase in Queue Length (Under-estimation of V/M Ratio)

	Level of Under-estimation														
Scenario	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
10	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4
11	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
12	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3
13	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

4. OBSERVATIONS

The following summarizes our observations which are based on the assumptions made for the scenarios tested in this study:

- Overall the change in delay is insignificant when less accurate data are used to calibrate the signal timing plan. The effect of over- or under-estimation of flow on total vehicle delays increase with the flow level. When flow is low, less than 1% of increase in delay is observed. When flow is moderately heavy, less than **4%** of increase in delay is observed. Significant increase in delay can be observed (above **10%)** only when the flow level is underestimated in the situation of a high level of flow. This is true for both intersections of two major streets and intersections of a major and a minor street.
- For a given flow level, the deterministic component **of** Newell's delay formula increases with cycle time while the stochastic component decreases with it. The deterministic component is more sensitive to the changes in signal timing settings than the stochastic component. Also, the influence of the deterministic component on total delay increases when the V/M ratio is reduced. Consequently, total delay is more sensitive to accuracy of flow estimation when V/M ratio is small.
- Stochastic fluctuations in arrivals have very little effect on the change in delay, the total number of stops, and the queue length. In all situations, the changes in delay and other measures of performance are less than 1% when the variance-to-mean ratio is over- or under-estimated, regardless of the flow level and the arrival characteristics of the intersections.
- Negative increase is observed in a number of places, suggesting that the optimal plan is inferior to the non-optimal one. A possible explanation of this phenomenon is the approximation nature of the optimization process which was discussed in an earlier section. The timing plan generated thereby could be suboptimal depending on the optimization technique used and the compromise made between the mathematical accuracy and computational convenience.
- A slight decrease in total number of stops and queue length is observed when the flow level is overestimated. This is reasonable because the cycle length designed with overestimated flow level is usually set higher than necessary. Consequently, the total number of stops is reduced.

- Underestimation of flow can also result in an increase in queue length and the number of stops. The increase in total number of stops is minor for critical intersections (less then 5 %) but large for non-critical intersections (above 10% when the measured flow deviates from the actual flow by 10%). Over 20% of increase in queue length can be expected when v/m ratio is very high for critical intersections, and over 40% of increase for non-critical intersections.
- In general, the performance of a signal timing plan is more sensitive to the accuracy in input data when applied to an intersection with balanced flow than to an intersection with unbalanced flow.

5. CONCLUSIONS AND RECOMMENDATIONS

In practice, data used to develop a signal timing plan can be subject to various levels of inaccuracy. This is also true with the use of on-line data. This study examines performance of signal timing plans when the data used to calibrate the plans deviate from the actual one due to over- or under-estimation.

For the error range of the input data considered in this study, our result indicates that the increase in delay, the number of stops, and queue length is fairly insignificant. The increase in delay and other measures is within 4% when the flow level used is over- or under-estimated within this range for a low or medium flow level. For the same level of over- or under-estimation, the increase in delay and other measures can be high only when the flow level is very high. The effect, however, is reduced for overestimation of flow, since the cycle length is restricted by an upper bound. Overall, underestimation of flow poses a more serious problem than overestimation of flow, and thus should be avoided in practice. The result applies directly to signal timing plans that consider long term average benefit. Caution should be exercised to interpret the result for full traffic responsive control strategies.

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