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# Effect of Skewed Signalised T–intersection on Traffic Delay

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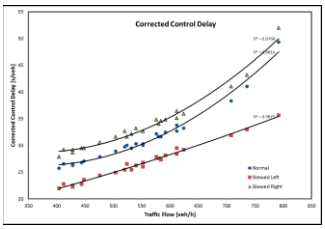
**Graphical abstract**




**Abstract**

Intersections are places where two or more highways intersect. Their performance dictates the performance of the rest of the traffic network. When two highways cannot intersect at right angles due to some geometric constraints, skewed intersection forms. Generally a traffic signal system is designed to control traffic movements at road intersections without considering the orientation of the intersection. Such an approach might lead to inaccurate assessment of operational performance of a signalised intersection because such a configuration influences turning radius and hence the vehicle's negotiation speeds. This paper describes the result of a study carried out to evaluate the effect of orientation of a signalised intersection on the control delay to vehicular traffic. The evaluation was carried out using aaSIDRA software, which was calibrated using the data collected from site. Two models of skewed intersection based on a normal T–intersection were simulated at minor approach at 45° (i.e. skewed to the left), and 135° (i.e. skewed to the right), respectively. The result of the analysis showed that delay to the motorists in the minor approach increases when the minor approach is skewed from left to right..

*Keywords*: Signalised intersection; skewed intersection; control delay

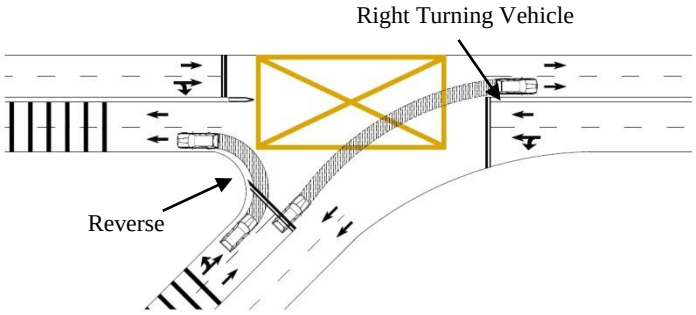


## 1.0 INTRODUCTION

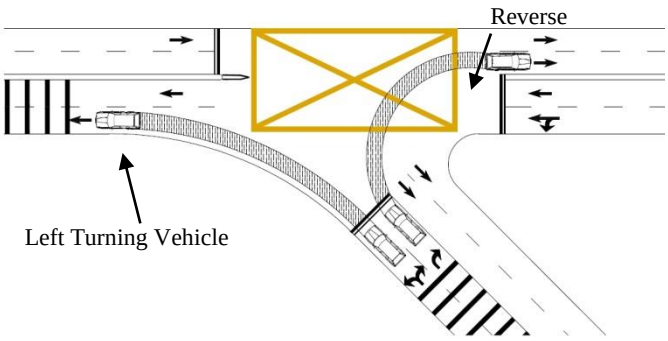
The most desirable two-road intersection angle is 90°. However, because of physical and other constraints, many roads meet at angles less than 90°. Such locations are referred to as skewed intersections, and the difference between 90° and the smallest acute angle between the intersection legs is referred to as intersection skew angle.

AASHTO green book [1] presents a policy design of intersections to minimize the deviation from a 90° intersection angle. The policy recommends a minimum intersection angle of 60° and this guidance has been adopted in the geometric design policies of many highway agencies. Configuration of intersection legs has a significant effect on the performance of the intersection due to the difficulties in turning movements of the vehicles, elongation of the crossings for pedestrians and reduction of sight distance.

Skewed intersection limits sight distance of the drives and creates difficulties of reaction within a proper time. On the skewed approaches of an intersection, the pedestrian crossing becomes longer than the normal perpendicular approach, which results in the exposure time of pedestrian on the crossing becomes longer, as well as the time required for the driver to clear the intersection increases. Right or left turning vehicle experiences a longer distance on a curved path to merge with the major traffic with a more limited vision, while the reverse turning vehicle faces difficulties while performing its turning movement on a sharper curve (Figure 1.1). These factors cause an extra delay of the vehicles at the intersection and consequently, it affects the overall performance of the intersection. The angle which approaches an intersection cross has a significant effect on the capacity, efficiency and safety of the junction.




(a) Minor road skewed to the left




(b) Minor road skewed to the right

**Figure 1.1** Possible orientations of the skewed intersections

## 2.0 BACKGROUND

Many studies concerning skew angle of intersection and its negative reflection on the safety performance have been accomplished, but still there is lack of sufficient information about the effect of skew angle on delay at signalised intersection, while delay is the major parameter for performance assessment of intersections.

In a case of a left–hand–driving system, the line of sight of the driver who stopped on the approach, which is skewed to the left side of the driver, is usually will be blocked by the left side of the vehicles. It was suggested that the stopping sight distance was varying with the speed of the through vehicles, thus the most appropriate angle was 70 degrees or more, depending on the speed of the through vehicles [2].

Three legged Y–intersection has a 50 percent higher accident rate than three legged T–intersection because of the influence of skew angle, which is higher in Y–intersections [3]. The observation angle of drivers at intersection had been studied by an Australian research. The study found that the increase of observation angle of drivers on the minor road (to look sideways or backwards in order to see vehicles on the major road approaching the intersection) had increased minor accident rates on the minor approach [4]. In another study, the impact of lateral visibility on safety of traffic movement at skewed intersection have been evaluated and the results suggested that an angle not less than 70 degrees for crossing manoeuvre, and an angle of not less than 7 degrees for merging movement should be used in order to preserve the safety of traffic movement at the intersection [5].

When two highways intersect at an angle less than 60 degrees, and realignment to increase this angle is not possible due to the constraints, some factors for determination of intersection sight distance may need adjustment. Angles greater than 60 degrees and closer to 90 degrees produce only a small reduction in visibility of the drivers [1] which can be neglected and no realignment is required. Figure 2.1 shows the change in sight distance triangle when the intersection legs are oriented from 90 degrees. All variables are as described in the AASHTO green book [1].

When two or more roadways intersect at an angle as close to 90 degrees, the exposure of vehicles at the intersection area to conflict is minimised, and the severity of potential conflict in turn is reduced. Skewed crossings produce restricted sight angles for the drivers, which may cause more difficulties for old drivers. The skewness of the intersecting approaches produces an extra distance at the intersection area for the vehicles to traverse [6] and this extra distance should be taken into consideration when designing the signal timing, as it may need some addition in all–red time, which is used by the vehicles to clear the intersection area. Figure 2.2 illustrates how skewed intersection approach can increase the distance to clear the intersection for both pedestrians and vehicles [7].

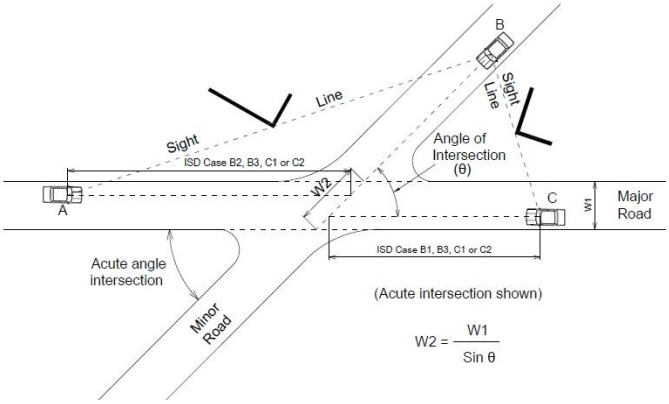



**Figure 2.1** Sight Triangles at Skewed Intersections

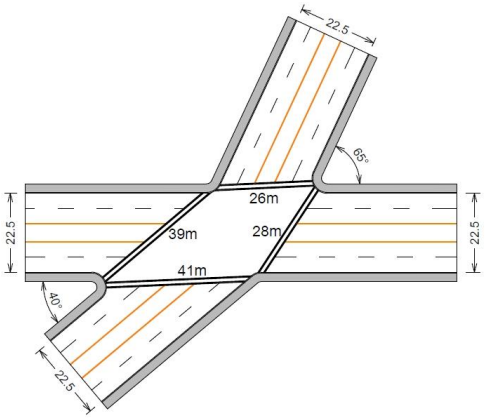



**Figure 2.2** Change in geometric measurements of intersection with different degrees of skewness

## 3.0 METHODOLOGY

This paper describes a study carried out to evaluate the effect of skewed angle, which exceeds 30 degrees at a signalised intersection on the control delay of the minor approach. The methodology of the study carried out can be divided into three parts (1) the observations of the actual traffic parameters at a signalised intersection (2) the modelling of the intersection, and (3) the evaluation of effect of skewness on delays. Part 2 and Part 3 of this study were based on the application of the aaSIDRA software [8], which is one of the commercial computer simulation package meant for the design and analysis of intersections.

### 3.1 Data Requirement and Site

The data required for the studies was grouped into two categories based on the purpose of the data collected (1) as an input data for the aaSIDRA software, and (2) for model calibration purposes.

#### *3.1.1 Input Data*

The basic input data required for the study includes the intersection geometric and traffic lane configuration characteristics, traffic signal settings and traffic flow data. The traffic flow data included all the necessary information about the traffic stream using the

facility which is basically the classified traffic turning volume expressed in terms of number of vehicles crossing the stop line of each approach in unit of time (usually every 15 minutes interval). Vehicle classifications were based on Malaysian practices [9].

### 3.1.2 Traffic Parameters for Model Calibration

Calibration of the aaSIDRA software for simulating signalised intersections based on local traffic conditions is an important procedure to ensure that the model replicates the real–world situation before it can be used in the analysis. The calibration was based on delay because it is one of the major performance measures of a signalised intersection. The data pertaining to the computation actual traffic delays collected from site was classified into the following types:

a) Vehicles in–queue: The collection of this data was based on the procedure provided by the Transportation Research Board (TRB)[10] where vehicles queued on the approach were counted for observed control delay measurement.
b) Non–delayed Vehicles: These were vehicles which had arrived at the intersection at the time the queue on the approach was discharged and the signal was still green. These vehicles were not delayed by the control system and were included in observed delay calculation procedure.

The observed approach control delays to the motorists were collected on site using the procedure suggested by TRB [10]. For a specific approach, the number of vehicles in queue were counted each 14 seconds interval (this included vehicles gained their speed but still not crossed the stop line), and this was continued for one hour each day of data collection. The observation hour was divided into four quarters to calculate delay for each 15 minute time interval. As we know control delay is composed of deceleration delay, stopped delay, queue move up delay, and acceleration delay. Control delay was then calculated from field–measured data through Equation (3.1) to (3.5) [10].

$$\boldsymbol{d = d_{vq} + d_{ad}} \tag{3.1}$$

$$\boldsymbol{d_{vq} = I_s * \left(\frac{\sum V_{iq}}{V_{tot}}\right) * 0.9} \tag{3.2}$$

$$\boldsymbol{d_{ad} = FVS * CF} \tag{3.3}$$

$$\boldsymbol{FVS = \frac{V_{stop}}{V_{tot}}} \tag{3.4}$$

$$\boldsymbol{V_{slc} = \frac{V_{stop}}{N_c * N}} \tag{3.5}$$

Where;
$d$ = total control delay (s/veh)
$d_{vq}$ = time in-queue per vehicle (s/veh)
$d_{ad}$ = acceleration/deceleration correction delay (s/veh)
$I_s$ = time interval between time-in-queue count (14sec.)
$\sum V_{iq}$ = sum of all vehicle-in-queue count (veh)
$V_{tot}$ = total number of vehicles arriving during the study period (veh)
$FVS$ = fraction of vehicles stopping
$CF$ = correction factor (From Table 3.1)
$V_{stop}$ = total count of stopping vehicles (veh)
$Nc$ = number of cycle surveyed
$N$ = number of lanes in the survey lane group
$V_{slc}$ = number of vehicles stopping per lane each cycle

**Table 3.1** Acceleration–deceleration delay correction factor, CF

| Free–Flow Speed | ≤ 7 vehicles | 8 – 19 Vehicles | 20 – 30 Vehicles[a] |
|---|---|---|---|
| ≤ 60 km/h | + 5 | + 2 | – 1 |
| > 60–72 km/h | + 7 | + 4 | + 2 |
| > 72 km/h | + 9 | + 7 | + 5 |

*Source:* Highway Capacity Manual 2000 [10] (A 16-2)

### 3.1.3 Site Selection

It is realized that a relatively accurate measurement of traffic delays may be obtained from an extensive field observations and large quantity traffic data. However, because of limitation in time and resources, the quantity of data to be collected for this study have to be compromised between a reasonable, realistic data collection effort and the need for adequate data for numerical analysis. Ideally the selection of the site to be used for data collection purposes should be based on the following criteria:

(a) good access and safety for the enumerators and equipment during the data collection process,
(b) good overhead vantage points for video recording purposes, and
(c) good sight distances (to ensure that the sight distances do not influence the interactions between drivers)

Unfortunately, signalised intersections in an urban area, which have all the criteria described above, were difficult to find. Therefore, the site selected for this study was a compromise between the criteria given above. After examining several intersections, an intersection at Jalan Kebudayaan in Skudai, Johor, Malaysia was selected as the case study. The site was a T–junction with approaches intersecting at an angle near to 90º which was proper for this study. The number of approach lane on each arm was two, and the traffic movements at the intersection were controlled by a vehicle–actuated traffic signal system.

A pilot study was carried out for several days in a week at different times each day to indicate the hours of the day when the number of vehicles queuing in the minor approach did not exceed 20–25 vehicle/lane/cycle. This is one of the requirements in the methodology, as provided in the Highway Capacity Manual 2000 [10].

## 3.2 Field Data Collection and Analysis

Traffic data collection process was carried out based on the procedure and requirements provided by the Highway Capacity Manual 2000 [10]. The manual provides a methodology for field measurement of control delay at signalised intersection. Video recording technique was used to record traffic data in the field for a total period of eight hours. The video camera was located on the building to record traffic scenes. The schematic diagram of the intersection and location of the video camera is shown in Figure 3.1.

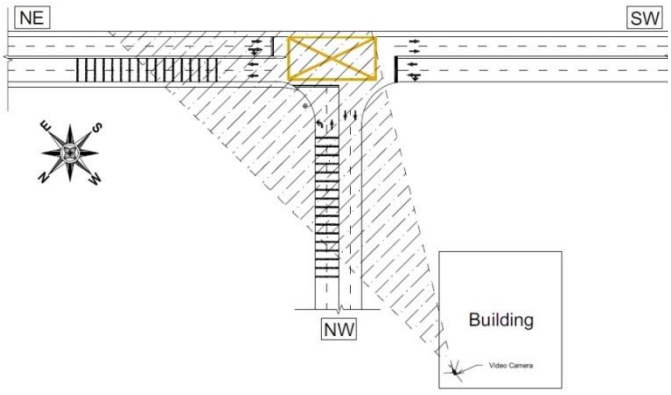



**Figure 3.1** Configuration of the intersection and position of the video camera

The position of the video camera was important in order to be able to obtain the required traffic information from the video record, such as traffic volume, turning proportion, speed, non-delayed vehicles and headway.

Data from the video records were extracted by utilizing Corel VideoStudio Pro X4 software and recorded in specific tables prepared for calculation of all required variables. The data was divided into 15–minutes intervals to deduce traffic volumes, and their associated average observed control delay per vehicle was obtained using the methodology outlined in the Highway Capacity Manual 2000 [10].

### 3.3 Modelling of Signalised Intersections

Analysis of the effect of skewness on traffic delays was based on the commercial simulation model of intersections known as aaSIDRA [8]. The studied signalised T–intersection was simulated using the aaSIDRA and used as the basis for comparisons with other configurations of a three–armed intersection. This same intersection was modelled again with the minor approach i.e. skewed to the left at 45º and skewed to the right. Figure 3.2 shows the configurations of the simulated intersection. The arm marked with 'N' was used for the case of skewed to the left and the arm marked with 'W' was for the case of skewed to the right.

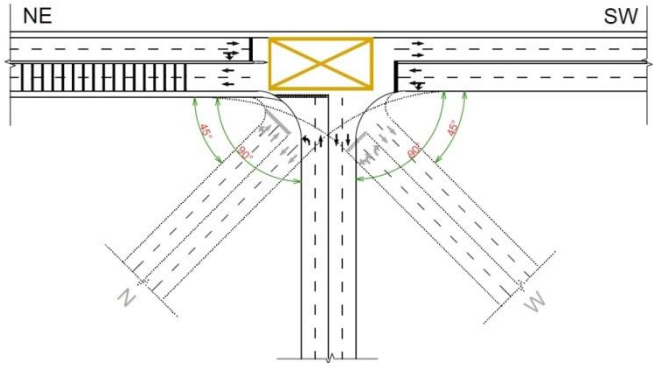



**Figure 3.2** Configuration of skewed intersections used in the study

To ensure the delays were not influenced by factors other than the orientation of the minor approach, the following criteria were used in the modelling process:

a) the existing traffic signal setting, i.e. a fixed–time system, is applied to all cases, and
b) the comparison of delay is based on a similar traffic characteristics at all intersections

## 4.0 RESULTS AND DISCUSSIONS

Results of data collection and operational analysis processes are presented and discussed in the following sections.

### 4.1 Traffic Characteristics

A total of 16,383 vehicles were counted entering the intersection during the study period. The average traffic compositions indicates that vehicles categorised as light vehicles (i.e. cars, light vans/utilities) are the major types of vehicles in the traffic stream, which constituted about 80% of the total traffic. This is followed by motorcycles, i.e. about 18%, and medium trucks and buses, which amounted to about 2%. The average hourly lane distribution of traffic on each approach is as illustrated in Figure 4.1.

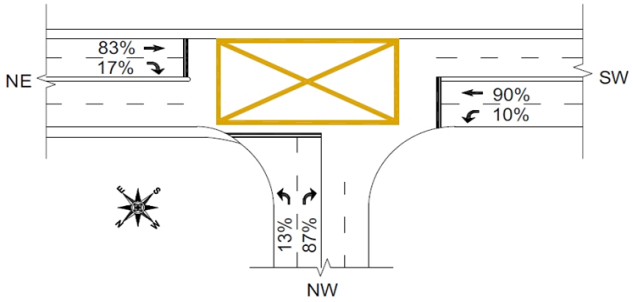



**Figure 4.1** Distribution of traffic volumes

Traffic signal data of the vehicle–actuated control system was collected simultaneously during the delay study period. Information of traffic signal data is summarised in Table 4.1. The free–flow speed of vehicles was measured on a segment of the road that was far enough from the intersection to avoid impact of the control system on the free-flowing vehicles. The measured average free-flowing speed was 42 km/h.

### 4.2 Characteristics of Control Delay

In this study, the control delay to vehicles on minor approach was used to calibrate the aaSIDRA software. A total of 4,406 vehicles were observed for delay study purposes. Table 4.2 illustrates an example of the observed control delay obtained from field measurement based on one hour data. All variables are as described in methodology.

The aaSIDRA software was used to calculate the control delay for each traffic volume data set. The data used as an input for the program was the same data (i.e. the average cycle length, traffic flow, speed, geometry etc.) which was used in the calculation of the observed control delay of the mentioned approach. Figure 4.2 shows the scatter plot of both observed and simulated control delays to vehicles in the minor approach.

It can be seen from Figure 4.2 that there was a significant difference between the simulated and observed delay for the same traffic characteristics. The aaSIDRA appears to over–estimate the actual delays experienced by the motorists in the minor approach. This conclusion is supported with a statistical t–test conducted to evaluate the significance difference between the two sets of data

(i.e. with a p–value of 9.95915 x $10^{-13}$, t–stat of –12.21 and t–critical of 2.0484).

It is believed that the significant difference between the observed and simulated delays was due to the existence of high percentage of motorcycles in the traffic stream. The aaSIDRA software did not consider motorcycles in the analysis. Motorcycles require shorter time to accelerate and decelerate. They can move to the head of the queue in between the queued vehicles and mostly they accelerate in the form of group into the intersection when the signal turns green. This had shortened the delay time of the motorcycles as they were not required to follow each other in a lane like other vehicles.

The aaSIDRA does not consider the effect of motorcycles in the software database. The only consideration is differentiating heavy vehicles from the rest of traffic volume by supplying input of percent of heavy vehicles. This means that motorcycles were considered to spend the same interval of time that is required by car in order to cross the intersection during green period. So, only heavy vehicles were taken into account to spend a different time interval to cross the intersection. Also in the procedure for estimating control delay in the field by HCM 2000, there is no special consideration for motorcycles, as all vehicles observed are of the same type. An important point to concentrate on is the time spent by each vehicle; cars, buses, lorries, motorcycles, etc, leaving the queue and clearing the intersection.

In determining control delay incurred by individual vehicle, queued vehicles were usually counted at specific interval of time; 14 seconds in this study. However, prior to the appearance of the green light, about one or two vehicles exit the intersection. Likewise, high proportion of motorcycles that usually stopped at the forefront also exit the intersection before the light turns green. As such, they were not considered in the counting which subsequently affects the average time required by each vehicle to leave the queue.

**Table 4.1** Average field–measured signal timing

| Approach | Green Period (sec) | | | Cycle Time (sec) | | | Amber (sec) | All–Red (sec) |
|---|---|---|---|---|---|---|---|---|
| | Max. | Min. | Average | Max. | Min. | Average | | |
| Northwest | 35 | 17 | 27 | 134 | 87 | 112 | 3 | 2 |
| Northeast | 41 | 16 | 28 | 133 | 106 | 116 | 3 | 2 |
| Southwest | 50 | 19 | 46 | 123 | 77 | 108 | 3 | 2 |
| | | | | | Average | 112 | | |

**Table 4.2** Observed control delay

| Time | | Volume (veh/15min) $V_{tot}$ | | Stop Vehicle Count $V_{stop}$ | Vehicle in Queue $V_{iq}$ | Free–Flow Speed, FFS | CF (sec) | FVS ($V_{stop}/V_{tot}$) | N | $N_C$ | $d_{vq}$ (sec/veh) | $V_{slc}$ | $d_{ad}$ (sec/veh) | Control Delay, d (sec/veh) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 04.30 – 04.45pm | R | 135 | 153 | 105 | 376 | 42 | 2 | 0.75 | 2 | 8 | 30.96 | 8 | 1.49 | 32.45 |
| | L | 18 | | 9 | | | | | | | | | | |
| 04.45 – 05.00pm | R | 135 | 156 | 110 | 413 | 42 | 2 | 0.80 | 2 | 8 | 33.36 | 8 | 1.60 | 34.96 |
| | L | 21 | | 15 | | | | | | | | | | |
| 05.00 – 05.15pm | R | 163 | 184 | 134 | 486 | 42 | 2 | 0.78 | 2 | 9 | 33.28 | 9 | 1.57 | 34.85 |
| | L | 21 | | 10 | | | | | | | | | | |
| 05.15 – 05.30pm | R | 172 | 198 | 143 | 770 | 42 | 2 | 0.79 | 2 | 7.8 | 49.00 | 10 | 1.58 | 50.58 |
| | L | 26 | | 13 | | | | | | | | | | |
| Total | | | 691 | 539 | 2045 | | | | | | | | | |

Note: R – right turning vehicles and L – left turning vehicles
All variables are as described in Section 3.1.2

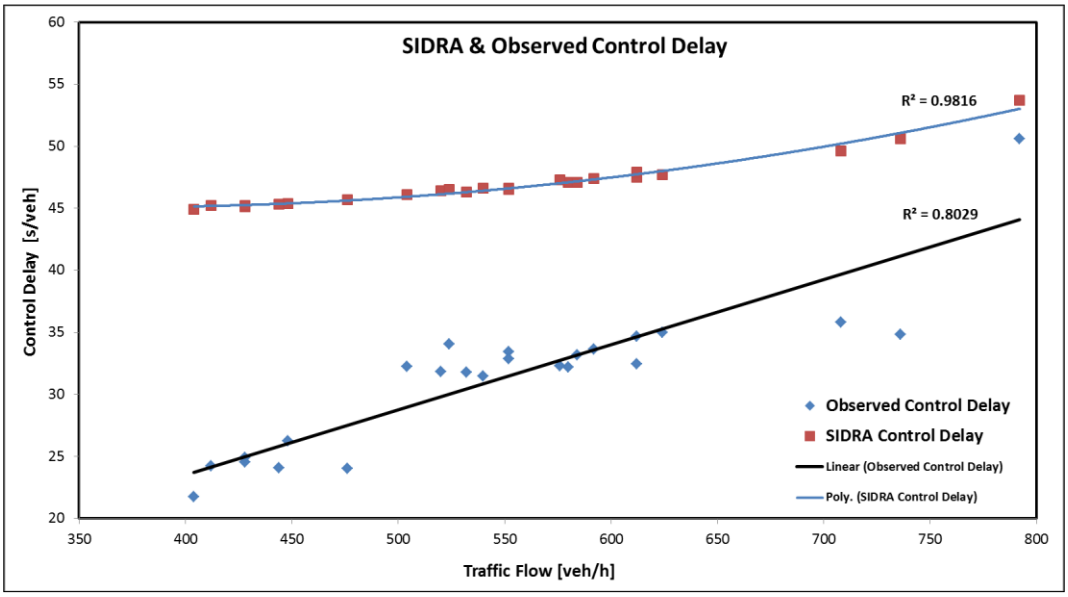



**Figure 4.2** Variations of aaSIDRA and observed control delays

## 4.3 Calibration of aaSIDRA

The significant difference between observed and calculated control delay values justified the necessity of calibrating the aaSIDRA simulation model before it can be used to evaluate the effect of skewness on traffic delays. Model calibration is actually a process in which model output is compared with collected of operations in practice. Where agreement is poor, parameter values and/or assumptions are adjusted to provide better agreement between observed and predicted values. The predicted delays using the aaSIDRA model were plotted against the observed values for a range of traffic flows as shown in Figure 4.3. The plots indicate that the control delay calculated by the aaSIDRA model can be adjusted to give an estimate of actual control delay for a particular volume of traffic, using the mathematical relationship between the observed and simulated delays as shown in Equation (4.1). This Equation (4.1) is applicable for a situation where the present of motorcycles is not more than 20% and they are not following a specific traffic queuing system.

$$\text{Actual Control Delay} = 2.6833 * D_{aaSIDRA} - 94.749 \text{ sec/veh} \quad (4.1)$$

Where $\text{Delay}_{aaSIDRA}$ is the delay estimated by the aaSIDRA model.

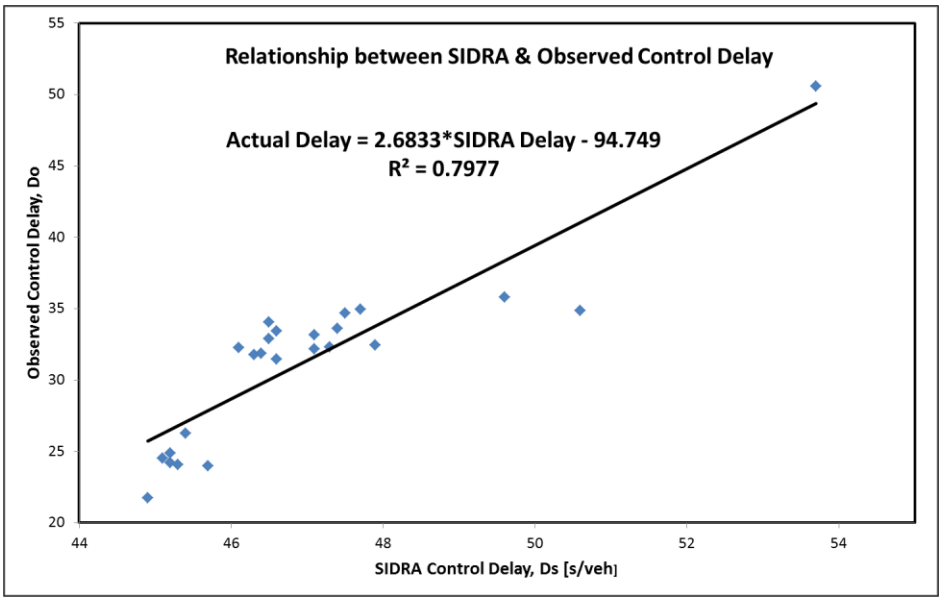



**Figure 4.3** Relationship between aaSIDRA and observed control delay

### 4.4 Effect of Skewed Intersection on Traffic Delays

The two models of skewed T–intersections were simulated using the 24 sets of traffic data collected for the reference intersection. Figure 4.4 shows the variations of control delays to the motorists on minor approach for the respective approach traffic flows. The analysis was based on the cycle time of 112 seconds and a green period of 46 seconds for the minor road traffic phase.

Results showed that when minor approach of the intersection was skewed to the left, the approach control delay incurred by the motorists in the minor approach was about 14.12 percent and 26.25 percent lower than the delays obtained for the normal T–intersection and for the skewed to the right intersection, respectively.

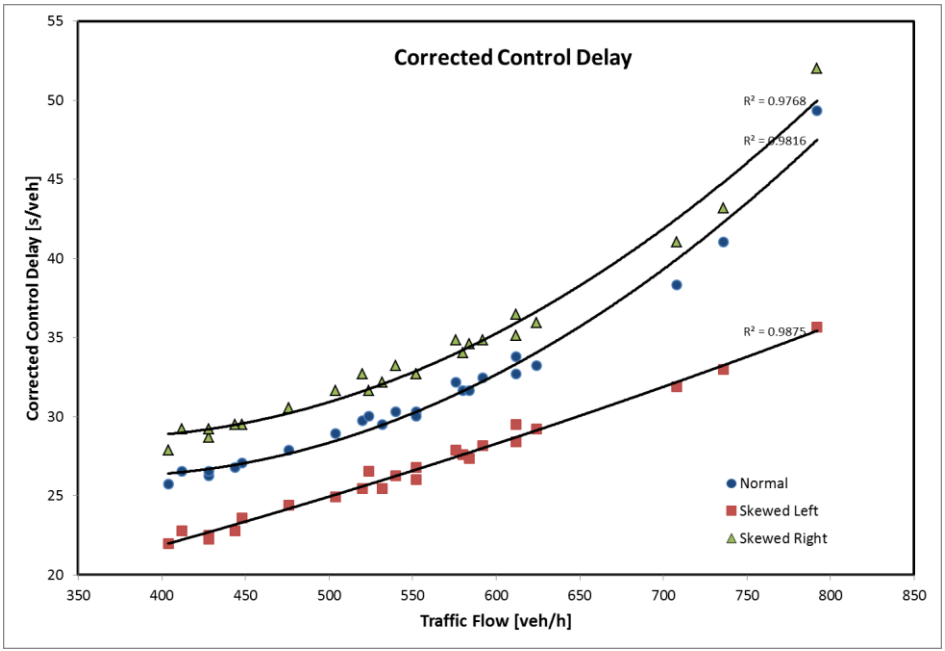



**Figure 4.4** Variations of control delays for three configurations of the T–intersection

In the case for the minor approach skewed to the right, it was found that the delay to motorists was about 8.31 percent higher than the values obtained for the case where the minor approach was perpendicular to the major road.

It appears that the control delay was influenced by the right turning vehicles. When the minor approach was skewed to the left, it was found that the delay incurred by the right turning vehicles was about 31 percent lower than the values for the normal approach condition. This was probably due to relatively large right–turning radius, which provides a smoother and easier turning manoeuvre to the right–turning vehicles. On the other hand, when the approach was skewed to the right, the right–turning vehicles experienced an extra delay of 5% of the normal condition. Skewing the approach to the right had caused a smaller turning radius which made it difficult for the right–turning vehicles to negotiate at high speed.

## 5.0 CONCLUSIONS

This paper described the result of a simulation study, which was carried out to evaluate the effects of skewed minor approach at a signalised intersection on control delay to the vehicles on that approach. Through field observations and appropriate simulation procedures, this study has reached the following findings:

a) The average control delay to the motorists was influenced by the turning radius.
b) In the case of the left–hand driving system, the average control delay to the motorist in the minor approach skewed to the left was lower than the value obtained for the minor approach set perpendicular to the major road. On the other hand, the average control delay to the motorist in the minor approach skewed to the right was higher than the values obtained for the minor approach set perpendicular to the major road and skewed to the left.
c) The application of aaSIDRA software for the analysis traffic performance at intersections under heterogeneous traffic flow in this study required calibration and validation, because it did not explicitly consider the presence of motorcycles in the traffic streams.

The finding from this study suggests that the design of traffic signal control setting should consider the turning radius explicitly since a larger turning radius will require the motorists to travel a longer distance to clear the intersection and on the other hand, a smaller turning radius will cause the motorists to spend a longer time before they can clear the intersection due to low travel speed.

### Acknowledgement

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