

Chapter 3- Methodology

3. 1. Study Objective

The objective of the study is to utilize the traffic information obtained from point surveillance detectors to estimate in real-time the travel time on arterial streets.

3. 2. Introduction

Real-time estimation of travel times on arterial streets can be conducted by using statistical methods, by using cross classification tables of traffic volume by time of day based on field data collection, and by using traffic flow theory that estimate the vehicle movements on a link that has a traffic light with known or estimated properties. I selected to choose the traffic flow theory method in order for the method to be generic and transferable to other cities and to be consistent with the method used in travel time estimation on freeways.

3. 3. Study structure

Figure 3-1 shows the layout of a typical link i on an arterial street bounded by two intersections controlled by traffic lights. The observed traffic flow direction is in the eastbound direction. Link $i-1$ is the upstream link of link i , and link $i+1$ is the downstream link of link i .

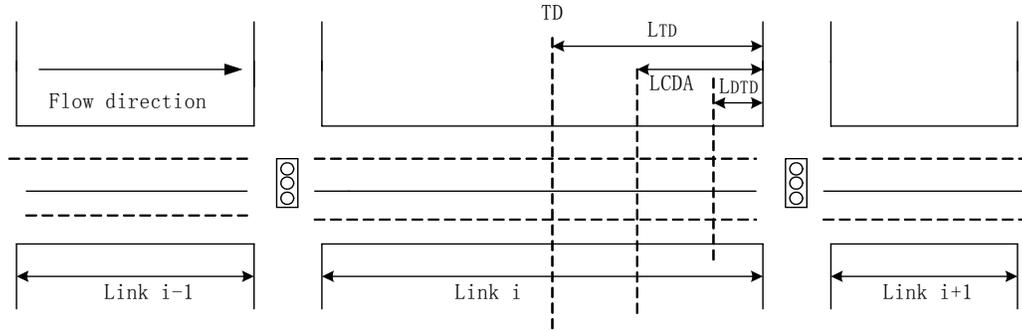


Figure 3- 1-Typical Layout of an Arterial Link

Other nomenclatures are defined below. Some of the variables are explicitly defined later on in the equations and in the text.

TD: Point Surveillance detector.

LTD : distance of the detector from the downstream intersection. The recommended location of the detector is at the midpoint of link i.

LDTD: Distance of the second detector from the downstream intersection. This detector is optional and was not considered in the development of the algorithms.

LCDA: Length of the vehicle queue from the downstream intersection.

When $LCDA \geq LTD$, there exits a blackout on the detector.

V: traffic volume detected at link i; (veh/h/ln)

C: capacity of the intersection; (veh/h/ln);

N_i : Number of lanes on link i;

CL: cycle length of the traffic light at the downstream intersection (sec);

g: green time at the downstream intersection for the traffic movement under consideration (secs);

r: red time of the intersection.(sec);

D_{si} : Departure or dissipation flow during green time on link i (veh/h/ln);

S_i : saturation or maximum vehicular flow on link i (veh/h/ln) during an hour of green time;

QL: Queue length (ft) = LCDA

Q_{t-1} : Initial queue for the time interval t (veh);

k_{id} : Vehicular density obtained from the detector (veh/mile);

k_q : Queue density (veh/mile);

d1: Uniform stopped delay (secs); (defined later on)

d2: Over-saturation and random delay (sec); (defined later on)

d3: Initial delay for the first vehicle in the observed group (secs); (defined later on)

d4: Initial stopped delay due to the initial queue.(secs) (defined later on)

L_i : the length of the link i;

Free flow speed: Speed limit on the street (mile/h);

Average Dwelling Time: the average time a vehicle dwells over the detector (sec/veh);

OCC_i: the occupancy at the loop detector for each observed group of vehicles;

$$OCC_i = (\text{average dwelling time}) * (\text{number of vehicles}) / (\text{Cycle length})$$

Other important definitions are stated below.

Blackout: Blackout condition exists if a car stays over the detector for an extended period of time. This condition produces a high value of average dwelling time at the detector which is approximately 0.7sec/veh (obtained from CORSIM simulation). To increase the accuracy of the algorithm, a blackout situation is declared when the average dwelling time is over 0.6sec/veh.

Time interval: normally the signal cycle length of the downstream intersection.

Observed vehicle group: It is the group of vehicles detected by the detector during the time interval when there is no blackout. If a blackout condition exists, the observed vehicle group is the group of vehicles detected by the detector on the upstream link during the time interval.

Travel time: the average travel time for each observed group of vehicles to traverse link i .

Determining the Volume of the Observed Group:

Since the detector can provide only traffic data for every minute (60 secs), then the observed volume or the vehicle group during the traffic light cycle length changes with the cycle length, especially if the cycle length is greater than 60 secs.

Therefore, we adjust the volumes detected by the sensor according to the remaining time differences between the detection time and the cycle length time.

This can be best illustrated first by using an example. Let us assume that we have an intersection with a cycle length of 100secs, and the detected volume is updated at every 60 secs.

The volume at time period t between 101 and 200 secs is calculated as follows:

From diagram below the following inequalities hold:

$$n*60 \leq (t-1)100 \leq (n+1)60, \text{ where } n, t-1, \text{ and } n+1 ; \text{ and}$$

$$k*60 \leq (t)100 \leq (k+1)60, \text{ where } k, t, \text{ and } k+1:$$

To get the volume at time interval 101-200

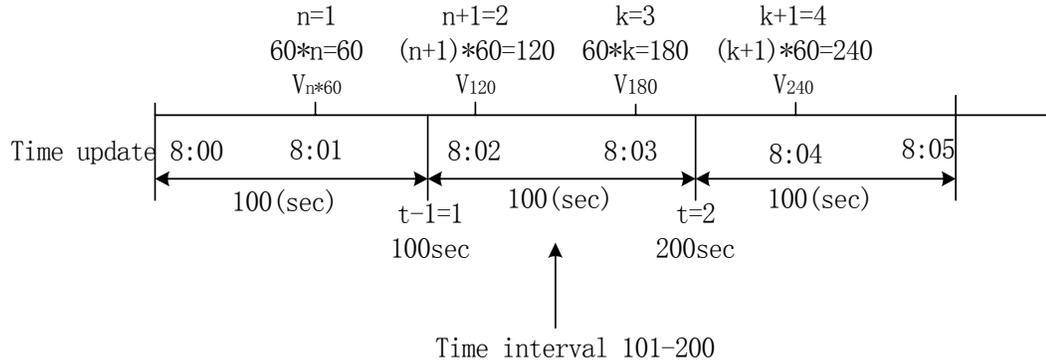


Figure 3- 2 Determining the Volume of the Observed Group

t is the observed time interval, and n*60, (n+1)60 are the closest values to (t-1)*100, and where k*60 and (k+1)60 are the closest values to (t)100. n and k are integer values.

Hence, the volume at time period t is:

If t=1

$$V_t = V_{60} + V_{120} \times \frac{100 - 60}{60}$$

otherwise

$$V_t = \frac{[(n+1) \times 60 - (t-1) \times 100]}{60} \times V_{(n+1) \times 60} + \frac{100 \times t - 60 \times k}{60} \times V_{(k+1) \times 60} + (k - n - 1) \times V_{k \times 60}$$

..... (Eq 3- 1)

To generalize the above procedure, the following equations are developed to address the various possibilities in Cycle Length (CL) for an update time t_{up} of 60 (secs) from the detector.

1. When update time ≤ cycle length ≤ 2*update times.

The equation is :

$$n * t_{up} \leq (t-1)CL \leq (n+1) * t_{up},$$

$$k * t_{up} \leq (t)CL \leq (k+1) * t_{up},$$

if $t=1$

$$V_t = V_{k(t_{up})} + V_{(k+1)(t_{up})} \times \frac{CL - t_{up}}{t_{up}}, \dots \text{(Eq 3- 2)}$$

Otherwise

$$V_t = \frac{[(n+1) \times t_{up} - (t-1) \times CL]}{t_{up}} \times V_{(n+1) \times t_{up}} + \frac{CL \times t - t_{up} \times k}{t_{up}} \times V_{(k+1) \times t_{up}} + (k-n-1) \times V_{k \times t_{up}}$$

..... (Eq 3- 3)

2. When $2 \times \text{update times} \leq \text{cycle length}$

$$n \times t_{up} \leq (t-1)CL \leq (n+1) \times t_{up},$$

$$k \times t_{up} \leq (t)CL \leq (k+1) \times t_{up},$$

if $t=1$;

$$V_t = \sum_{h=k}^t V_{h(t_{up})} + V_{(k+1)(t_{up})} \times \frac{CL - t_{up}}{t_{up}}$$

Otherwise;

If $k-n-1=1$

$$V_t = \frac{[(n+1) \times t_{up} - (t-1) \times CL]}{t_{up}} \times V_{(n+1) \times t_{up}} + \frac{CL \times t - t_{up} \times k}{t_{up}} \times V_{(k+1) \times t_{up}} + (k-n-1) \times V_{k \times t_{up}}$$

If $k-n-1=2$

$$V_t = \frac{[(n+1) \times t_{up} - (t-1) \times CL]}{t_{up}} \times V_{(n+1) \times t_{up}} + \frac{CL \times t - t_{up} \times k}{t_{up}} \times V_{(k+1) \times t_{up}} + V_{k \times t_{up}} + V_{(k-1) \times t_{up}}$$

Hence, the final equation is:

$$V_t = \frac{[(n+1) \times t_{up} - (t-1) \times CL]}{t_{up}} \times V_{(n+1) \times t_{up}} + \frac{CL \times t - t_{up} \times k}{t_{up}} \times V_{(k+1) \times t_{up}} + \sum_{h=0}^{k-n-1} V_{(k-h) \times t_{up}}$$

..... (Eq 3- 4)

Travel Time Update at every 2 minutes (120seconds):

If we chose to update the traffic data from the detector at 2 minutes interval

instead of one minute interval, then the observed volume or vehicle group during the traffic light cycle length is determined by the following formulae:

If cycle length (CL) is assumed to be 100 seconds, the observed volume at the first cycle interval is:

$$(V_{120}) * 100 / 120$$

For other cycle intervals, we adjust the detected volumes according to the remaining time differences between the detection time and the cycle length time.

Following the previous example, the volume at time period t is calculated as:

$$n * 120 \leq (t) 100 \leq (n+1) 120,$$

$$V_t = \frac{[(n) \times 120 - (t - 1) \times 100]}{120} \times V_{n \times 120} + \frac{100 - [(n) \times 120 - (t - 1) \times 100]}{120} \times V_{(n+1) \times 120}$$

.....(Eq 3- 5)

This equation can be equally applied when **cycle length < update time** as;

$$n * t_{up} \leq (t) CL \leq (n+1) t_{up},$$

if t=1

$$V_{CL} = V_{up} \times \frac{CL}{t_{up}}$$

For all other time updates :

$$V_t = \frac{[(n) \times t_{up} - (t - 1) \times CL]}{t_{up}} \times V_{n \times t_{up}} + \frac{100 - [(n) \times t_{up} - (t - 1) \times CL]}{t_{up}} \times V_{(n+1) \times t_{up}} \dots\dots (Eq 3- 6)$$

These calculations of observed volumes for different cycle length are also described in detail in the application section of this report.

Time Progression of vehicles through a Signalized Intersection:

The following discussion is provided to illustrate the time it takes a group of

vehicles to traverse through a signalized intersection after being detected by the surveillance system.

The incoming detected vehicles during the time interval (which corresponds to the signal cycle length of the downstream intersection) represent the observed group of vehicles. The average travel time of this group of vehicles represents the travel time component encountered by the vehicles to traverse the signalized intersection during the signal cycle length.

At time t_0 ,

The position of vehicles at time t_0 is shown in Figure 3-3:

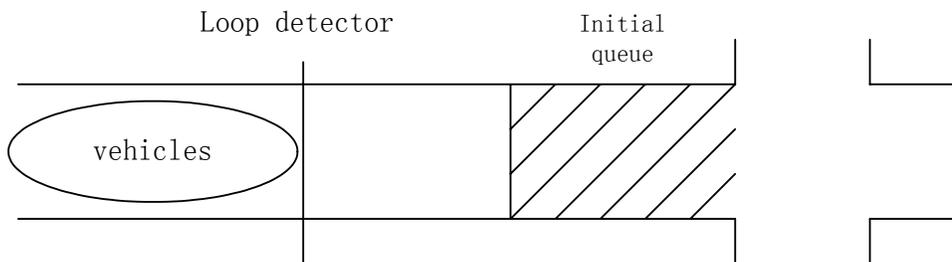


Figure 3- 3 Time t_0

At time $t_0 + \text{Cycle length}$,

The observed group of vehicles is composed of the first vehicle that passes the loop detector to the last vehicle that passes the loop detector during the time $t_0 + \text{Cycle length}$, as shown in Figure 3-4

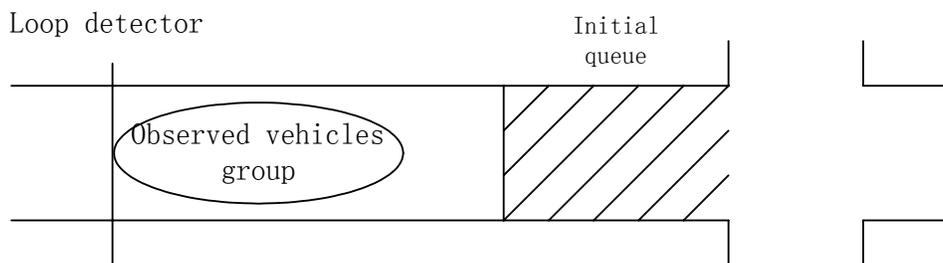


Figure 3- 4 Time $t_0 + \text{Cycle Length}$

At time t_1

At time t_1 , the first vehicle in the observed group reaches the end of the initial vehicle queue. The initial vehicle queue represents the vehicles that did not dissipate from the previous cycle length or time interval, as shown in Figure 3-5.

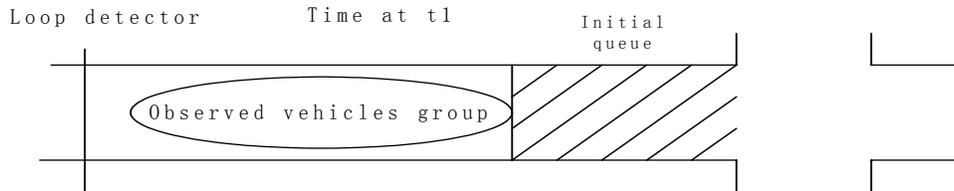


Figure 3- 5 Time t_1

At the time t_1+d_3

At time t_1+d_3 , (d_3 is dissipation time for the queue), the observed group of vehicles reaches the intersection as shown in Figure 3-6. The time t_1+d_3 may be in the middle of a cycle length.

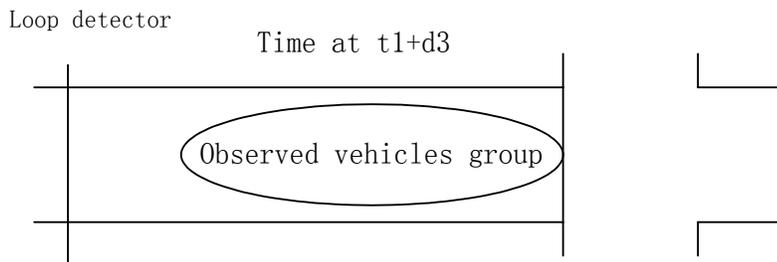


Figure 3- 6 Time t_1+t_3

At the time t_1+d_3+CL

When the volume of this observed group is smaller than the capacity of the intersection, it encounters only uniform stopped delay at the intersection which is caused by the red time phase. All the vehicles in this group may dissipate the intersection during the time of the signal cycle length, as shown in Figure 3-7.

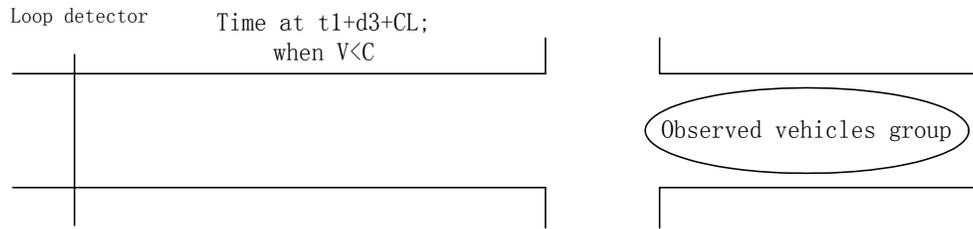


Figure 3- 7 Time t_1+d_3+CL

When the volume of this observed group is greater than the capacity of the intersection, certain vehicles in this observed group can not dissipate the intersection during the signal cycle length due to the limited capacity of the intersection. This group of vehicles is then separated into two parts; part A and part B, as shown in Figure 3-8. There are $C * CL$ vehicles in part A which can clear the intersection during the cycle length. Vehicles belonging to part A encounters the uniform stopped delay. There are $(V-C)*CL$ vehicles in part B which can not dissipate during the time of a cycle length. The time it would take vehicles in part B to dissipate the intersection are measured by the over-saturation delay for this observed group of vehicles. Initial queue delay, uniform stopped delay, and over-saturation delay are all explained in detail in Chapter 4.

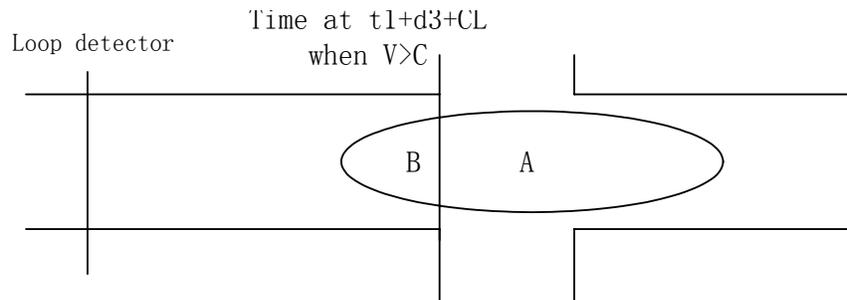


Figure 3- 8 Over-Saturation Condition

3. 4. Basic Concepts

The travel time on an arterial link for a particular time interval is made up of two components. The first component is the delay encountered by the travelers at the signalized intersection which is referred to as control delay, and the other component is the travel time on the regular stretch of the arterial link before arriving to the intersection. The control delay is very much dependent on the intersection capacity and its dissipation flow rate.

The basic concepts of determining intersection capacity are presented first. They are based on the Highway Capacity Manual of 2000.

3. 4.1 Intersection capacity

If the intersection is a pre-timed signal intersection, its capacity is:

$$C = S \times \frac{g}{CL} \dots\dots\dots(\text{Eq 3- 7})$$

Where

C=capacity of lane group(veh/h/ln)

S=saturation flow rate for through lane (veh/h/ln) as explained below, and

g/CL=effective green time to cycle length ratio for lane group.

3. 4.2 Saturation flow rate (departure flow rate in green time)

A saturation flow rate for each lane group is computed according to Equation 3-8.

$$S = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} \dots\dots\dots (\text{Eq 3- 8})$$

Where: S = saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (veh/h);

s₀ = Base saturation flow rate per lane per hour of green time (pc/h/ln);

It is estimated in HCM to be 1800 pc/h/ln.

N = Number of lanes in lane group;

f_w = Adjustment factor for lane width;

f_{HV} = Adjustment factor for heavy vehicle in traffic stream;

f_g = Adjustment factor for approach grade;

f_p = Adjustment factor for existence of a parking lane and parking activity adjacent to lane group;

f_{bb} = Adjustment factor for blocking effect of local buses that stop within intersection area;

f_a = Adjustment factor for area type;

f_{LU} = Adjustment factor for lane utilization;

f_{LT} = Adjustment factor for left turns in lane groups;

f_{RT} = Adjustment factor for right turns in lane groups;

f_{Lpb} = Pedestrian adjustment factor for left-turn movements; and

f_{Rpb} = Pedestrian-bicycle adjustment factor for right-turn movements.

I am not planning to request all this information for each intersection. I will approximate it to be 1800 veh/hr/ln in the algorithms.

3. 4.4 The Total Travel Time on a Link:

The total travel time on a link is the summation of the travel time encountered by the average traveler before reaching the intersection and the travel time encountered at the intersection which is made up of average uniform stopped ($d1$), plus saturation and random delay ($d2$), plus initial stopped delay ($d4$).

3. 4.4.1 Travel Time Without Queue:

$$Travel - time = \frac{L}{speed_by_detector} + d1 + d2 + d4 \dots\dots\dots(Eq\ 3- 9)$$

Where;

L=length of the link;

When there is a blackout on the detector, the detected volume does not represent the incoming volume. In this case, an algorithm is developed to estimate the travel time based on the upstream link departure volume.

3. 4.4.2 Travel time with a queue but without blackout:

$$Travel - time = \frac{L_{TD} - QL}{speed_by_detector} + \frac{L - L_{TD}}{speed_limit} + d1 + d2 + d4 \dots\dots\dots(Eq\ 3- 10)$$

3. 4.4.3 Travel time with blackout (i.e. $QL > L_{TD}$) :

$$Travel - time = \frac{L - QL}{speed_limit / 2} + d1 + d2 + d4 \dots\dots\dots(Eq\ 3- 11)$$

The travelers arriving at the queue will have varying speed ranging from zero to full speed. Hence, an average speed is considered by dividing the detected speed by 2.

3. 4.5 Downstream Conditions of the Signalized Intersection

The number of lanes on the downstream link as well as the vehicle queue of the downstream link will affect the travel time on the link under consideration. A drop in number of lanes in the downstream link and when the queue of the downstream link reach the intersection, it will reduce the dissipation rate at link i and consequently the travel time to traverse it.

3. 4.6 Travel Time Estimation Sequence in the Network

In the arterial street network, the sequence of observed links is from the

downstream link to the upstream link.

3.4.7 Method Adopted for Travel Time Update

The volume detected by the detector is updated every 1 minute. Hence, the travel time for the network is updated every 1 minute. Since the travel time component for traversing the signalized intersection is controlled by the signal cycle length, we devised the following method that updates the travel time every one minute, yet taking into consideration the signal cycle length.

When the cumulative cycle length of the intersection is greater than 1 minute, the update time for the link upstream of this intersection is done at the end of the next minute. When the cumulative cycle length of the intersection is lower than 1 minute, the update time for the link upstream of this intersection is done at the end of this minute.

An example is provided in Figure 3-9 to explain this method using a series of intersections with the following cycle lengths:

Intersection 1: 90sec

Intersection 2: 60 sec

Intersection 3: 45 sec

Intersection 4: 120 sec

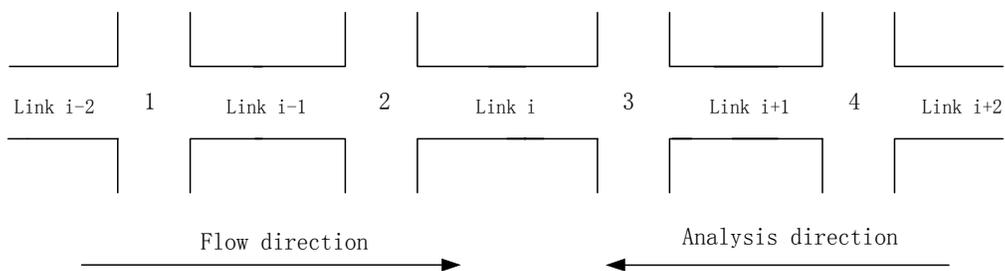


Figure 3- 9 Example for Travel Time Update

Let us assume that the observed travel time starts at 8:00:00 a.m.

At 8:01:00,

Travel time on link $i+1$ remains the same as the travel time calculated at 8:00:00, since the cycle length at intersection 4 is greater than 1 minute. For link i , the calculated travel time for a cycle length of 45 seconds, will be at time 8:00:45. However, it is transferred to be the travel time at 8:01:00 since the cycle length is less than one minute and the time update occurs at 1 minute interval. Travel time on link $i-1$ will be updated at 8:01:00, since its cycle length is 1 minute. Time on link $i-2$ will be the same as that of 8:00:00 since its cycle length is 90 seconds.

Tables below show the logic for times 8:01:00, 8:02:00, and 8:03:00.

Table 3-1 Time 8:01:00

Time	Link	Cycle length(sec)	Travel time at
8:01:00	$i+1$	120	8:00:00
8:01:00	i	45	8:00:45
8:01:00	$i-1$	60	8:01:00
8:01:00	$i-2$	90	8:00:00

At 8:02:00

Following the same rules as stated above;

Table 3-2 Time 8:02:00

Time	Link	Cycle length(sec)	Travel time at
8:02:00	$i+1$	120	8:02:00
8:02:00	i	45	8:01:30
8:02:00	$i-1$	60	8:02:00
8:02:00	$i-2$	90	8:01:30

At 8:03:00

Table 3-3 Time 8:03:00

Time	Link	Cycle length(sec)	Travel time at
8:03:00	i+1	120	8:02:00
8:03:00	i	45	8:02:15
8:03:00	i-1	60	8:03:00
8:03:00	i-2	90	8:03:00

3. 4.8 Computing the Turning Movement Volume at Large Intersections

When there is a blackout at the loop detector, the traffic information detected by the loop detector is not reliable. In this situation, we estimate the travel time on link i based on the volume obtained from the upstream link. But the turning movement has effect on the incoming volume estimation especially at a big intersection, whose four approach links are all arterial streets as shown in figure below. Thus, the incoming volume for link i, is the volume detected by link i-1 + turning on flow – turning out flow. “The turning on flow – turning out flow” needs to be determined. Let $V_{turn} =$ “the flow of turning on” – “the flow of turning out”.

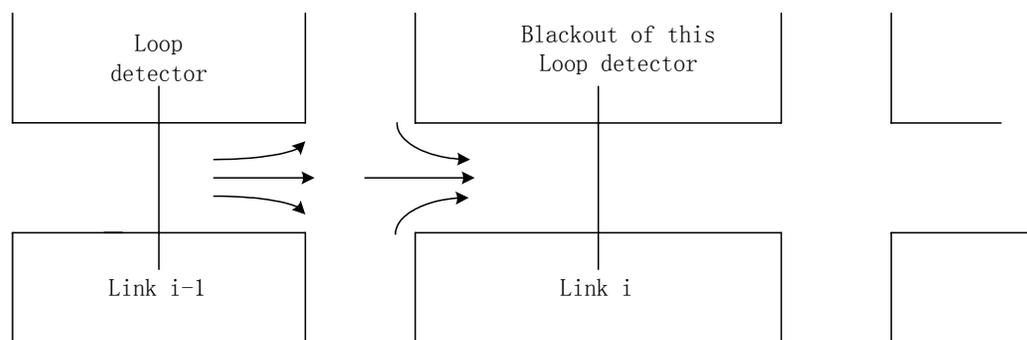


Figure 3- 10 Turning Movement Volume

Basically, the difference between the total volume detected by loop detectors of link i and link i-1 would provide a good approximation of V_{turn} .

We can select a time period t-1 before the time period t when a blackout on link i

is detected. Let V_i^{t-1} be the volume detected on link i during time period t-1, and V_{i-1}^{t-1} be the volume detected on link i-1 during time period t-1. Then, $V_{turn} = V_i^{t-1} - V_{i-1}^{t-1}$. But the result is not reliable because it will take several seconds or up to a minute for a vehicle to travel from the location of detector on link i-1 to the location of detector on link i. The way to reduce this error is to include as much as observed time periods as possible before the blackout took place. The error for a bigger observation time is smaller than a smaller observation time.

Thus, we use 10 time periods as the observation time duration.

Assume the blackout happened at time t. $\sum_{n=0}^{10} V_i^{t-n}$ is the total number of vehicles

counted by the loop detector at link i during 10 minutes before time t. $\sum_{n=0}^{10} V_{i-1}^{t-n}$ is the

total number of vehicles counted by the loop detector at link i-1 for the same 10 minutes before time t.

If $\sum_{n=0}^{10} V_{i-1}^{t-n} \leq (\text{capacity of link } i-1) * 10/60$ of link i-1, then

$V_{turn} = \sum_{n=0}^{10} V_i^{t-n} - \sum_{n=0}^{10} V_{i-1}^{t-n}$. If $\sum_{n=0}^{10} V_{i-1}^{t-n} > (\text{capacity of link } i-1) * 10/60$ of link i-1,

then $V_{turn} = \sum_{n=0}^{10} V_i^{t-n} - C_{i-1} \times \frac{10}{60}$.

If V_{turn} is positive, it means that the inflow into link i from the side streets is greater than the outflow into the side streets from link i-1. The opposite is true if V_{turn} is negative.

In order to deal with realistic values of V_{turn} in small periods, we chose to calculate the percent of turning movements designated as $t\%$. It is calculated as:

$$t\% \text{ is } \frac{V_{turn}}{\sum_{n=0}^{10} V_{i-1}^{t-n}}, \text{ when } \sum_{n=0}^{10} V_{i-1}^{t-n} \leq (\text{capacity of link } i-1) * 10/60$$

or,

$$t\% = \frac{V_{turn}}{C_{i-1} \times \frac{10}{60}}, \text{ when } \sum_{n=0}^{10} V_{i-1}^{t-n} > (\text{capacity of link } i-1) * 10/60 \text{ of link } i-1,$$

Appropriate Time Period for Selecting the Value of t%

As discussed above, we selected 10 periods backward from the time a blackout is declared to calculate the value of t%. However, this procedure may result in uneven multiples of the cycle length update periods (such as 100 secs. cycle length vs. 60 secs. volume update from the detector), which would make the downstream volume not to coincide exactly with the upstream volume for these time periods; unless an integer multiple of the cycle length is considered.

For example, the volume information from the detector is updated every 60 seconds, and the cycle length of the intersection is 100 seconds. We can not calculate the t% based on the volume data obtained in 60,120,180 seconds since they represent the times in the middle of the cycle lengths, which may include red time periods and cause an error in the estimation procedure between the volume detected at link i-1 and the volume detected at link i. Hence, we use appropriate integer multiples of the cycle length which in this case are 5, 10 and 15 that result in 300seconds, 600 seconds, or 900 seconds, this method can be generalized by considering $N \times 60/100$ to be an integer.

If the above time period selection procedure for t% (before the blackout happens)

is not acceptable, we can find an acceptable $t\%$ from previous or historical blackouts for the same link.

The next chapter describes the computations of the signal control delays.