SATURATION FLOW RATE AND PASSENGER CAR EQUIVALENTS AT SIGNALIZED INTERSECTIONS IN KOREA

Dong I. Ha
Senior Researcher
The Korea Transport Institute
968-5 Daechi-dong, Kangnam-ku
Seoul 135-280, Korea
Fax : +82-2-538-1391

abstract: It is one of the efficient ways to estimate the capacity of signalized intersection approaches by using the saturation flow rate. To determine the saturation flow rate, two major concerns were considered : (1) Saturation discharge headway, (2) Start-up lost time and saturation queue position. With the specific results of the above two terms, an additional consideration for passenger car equivalents was made. Since PCE value is another key factor in capacity analysis at signalized intersections. Important results were also compared with other analysis results such as US Highway Capacity Manual, Australian Capacity Manual, Swedish Capacity Manual, and so on.

1. INTRODUCTION

Currently, many metropolitan areas in Korea are faced with severe traffic congestion problem and traffic engineers endeavor to mitigate congestion. For urban traffic improvements, the estimation of signalized intersection capacity is to be one of the major elements to be considered. The 1985 USHCM recommended a methodology of capacity analysis using the saturation flow rate with geometric, traffic, and signalization conditions.

This research presents the analytic method of determining the saturation flow rate of singnalized intersections. Vehicle discharge rates during green time were collected and analyzed. Based upon the field survey, saturation discharge headway and saturation queue position were studied. In addition, passenger car equivalents were also determined to analyze the impact of heavy vehicles at signalized intersections.

2. DEFINITIONS AND ISSUES

2.1 Capacity of Signalized Intersection

In urban area, capacity of signalized intersection is important factor in analyzing arterial and network system, and influences directly to the analysis results. The capacity is determined by various road and traffic conditions such as grade, lane width, percent of heavy vehicle, green to cycle ratio, etc. Among them, the saturation flow rate and PCE are the fundamental parameters in estimating the signalized intersection capacity.

The 1985 USHCM is also based on the concept of saturation flow to analyze the capacity at signalized intersection. The saturation flow rate is the number of vehicles that could enter the intersection for the subject lane group under prevailing conditions with 100% of green time. It is generally expressed in terms of vehicles per hour of green time.

$$s = s_0 \times N \times f \tag{1}$$

where s = saturation flow rate (vphg)
s_0 = ideal saturation flow rate per lane (pcphgpl)
N = number of lanes in the lane group
f = adjustment factor.

And the capacity of a given signalized intersection can be stated as

$$c = s \times (g/C) \tag{2}$$

where c = capacity (vph)
g/C = ratio of effective green time to cycle length

The fundamental concept of saturation flow is extracted from the study of discharge of vehicles across the stop line at an intersection during green period. The headway is related to flow rate in traffic stream, and saturation headway is a critical parameter in describing the saturation flow rate. When green time begins at intersection, the first several vehicles consume more time to start and accelerate to the running speed, but after a few seconds the vehicle in queued state discharges in a constant rate. The constant rate is the saturation headway.

If it is assumed that each vehicle entering the intersection consumes the saturation headway, then the number of vehicles that can enter the intersection in a lane may be computed as

$$s_0 = \frac{3,600}{h} \tag{3}$$

where s_0 = ideal saturation flow rate (pcphgpl)
h = saturation headway.

2.2 Ideal Saturation Flow Rate

Ideal saturation flow rate is defined as the flow in PCE per hour under ideal traffic and roadway conditions. The following conditions are allowed as the ideal conditions in the USHCM :

. always green
. 3.6m lane width
. level grade
. no curb parking
. 0% heavy vehicle
. 0% right and left turns
. non CBD area
. no bus blockage.

Field observation of ideal saturation flow rate is very difficult, because ideal conditions are rarely found in reality. Thus, the USHCM suggests that ideal saturation flow rate may be modified based on local observations. There are limitations to collect desired data in Korea, since the lane width is usually in a range of 3.0 to 3.3m. It is also difficult to find out traffic condition that has enough demand with sufficient green time in non-CBD area. Therefore, the ideal saturation flow rate was determined based upon the possible ideal condition which is to be gathered in Korea.

2.3 Passenger Car Equivalents

As well known in the relevant literatures, PCE is a good indicator to quantify the impact of heavy vehicles in calculating the signalized intersection capacity. It is defined as the number of passenger cars that are displaced by a single heavy vehicle of a particular type under prevailing roadway, traffic, and control conditions. However, it is clear that PCE value can not be fixed as one value but variable greatly depending upon the given conditions. In the intersection capacity analysis, current PCE value suggested by the USHCM has following issues :

(1) The PCE value used in USHCM is 1.5, but there is little quantitative information on the effects of lane in traffic stream;
(2) There are differences in vehicle size, performance, and loading capacity by area and country;
(3) Driver characteristics are another important factor to be applied in PCE value adjustment;
(4) Only one PCE value is suggested in estimating the capacity. Supplemented information is requested by classifying the vehicle type.

3. METHODOLOGY

3.1. Saturation Headway

Two regression analysis methods were investigated to estimate the saturation headway in this study, which is linear regression analysis based on the constant headway and non-linear regression model based on the exponential reduction of headway.

1) Linear Regression Model

This assumes that there is a linear relationship between the intersection stop line crossing time of each vehicle. This kind of model is expressed in a simple linear regression model.

Such a simple model assumes that the intervals of the first several vehicles passing the stop line are comparatively large due to driver's reacting to the signal, but after that the headway is treated as "constant rate". That is, if the start-up lost time is not consumed in addition to headway, then the saturation headway is estimated from the vehicle discharge.

If the field observation of vehicle discharge headway is well corresponding to the theory of linear regression analysis, there are several advantages in using this simple model: it is convenient to decide the saturation queue position, saturation headway, and start up lost time at once.

2) Non-Linear Regression Model

The regression function of non-linear regression model using an exponential function can be expressed as

$$Hx = \exp(ax+b) + c \tag{4}$$

where Hx : headway of vehicle x in queue
x : position of vehicle in queue
a : negative parameter
c : saturation flow rate headway.

The non-linear regression model adopts the headway as a function of exponent reduction, for headway of discharged vehicle in queue reduces exponentially and then converges into a straight line at point c. Based upon estimated values of a, b, and c, the characteristics of vehicle discharge at signalized intersection can be explained.

The methodology to determine the saturation flow rate by the regression analysis is summarized as

1) Saturation headway is achieved based on the assumption that discharge rate of vehicle is constant after the first several vehicles discharge in the queued state.
2) But saturation headway depends on the geometric and traffic conditions. Thus, it would not be constant but rather various in the field.
3) Through the use of regression analysis model, however, the convergence value for saturation headway can be estimated from field observations, and then saturation flow rate is calibrated.

3.2. Saturation Queue Position

To measure the saturation headway, it is required to find the queue position at which start-up lost time ends. Therefore, the method to determine the saturation queue position is to be consistent to that of saturation headway or saturation flow rate. Various techniques are available in determining the saturation queue position. This study considered followings :

1) Based upon field observation of headways, the regression line is estimated then the saturation queue position is decided where the queue position has the best coefficient of determination(R^2).

2) Based upon the hypothesis testing for parameter B(queue position), saturation headway can be expected if null hypothesis B=O is not rejected.
3) Based upon information of headways, the investigator can expect the saturation queue position when queue position converges into point c in non-linear regression model.
4) Based upon the plots for the time of vehicle crossing the stop line versus queue position, the investigator decides the saturation queue position which has the best coefficient of determination(R^2) in regression analysis.
5) Using the multiple comparison method based on ANOVA experiment.

After testing five methods, multiple comparisons procedure in ANOVA was chosen to determine the saturation queue position. And, Duncan's Test was also used. When null hypothesis H_o is rejected, the investigator will usually want to know the differences from another. A method for carrying out this analysis is a multiple comparison procedure. Duncan's Multiple Range Test is one of such procedures in statistics, which involves the use of a statistic Q called studentized range statistic :

$$|a_i - a_j| > Q^1\sqrt{\delta^2/n} \tag{5}$$

where ai = the mean of observations for the ith treatment
Q^1_2 = statistic value from significant studentized range table
δ^2 = variance
n = the number of observations.

3.3 Passenger Car Equivalents

Two methods are generally used in estimating the PCE value at signalized intersection, namely (1) Simulation of intersection, (2) Measuring headways for various vehicle types in the field and using regression analysis. Although the simulation has several advantages, it requires detailed informations and some of the individual mechanisms. Thus, the regression analysis was selected for estimating PCE values in this research, based upon the field data.

The objective of multiple regression analysis is to build a probabilistic model which related one dependent variable to more than one independent or predictor variable. Based upon this concept, D. Branston set the passenger car flow rate as a dependent variable and replaced saturation flow rate, lost time, and PCE value with independent variables.

Bronston's model might be useful in determination of PCE value because it uses time T (duration of measurement) as a variable to estimate saturation flow rate and PCE at a same time. However, some questions where found in using a variable T, so this research presented the modified regression model for determination of PCE value after performing detailed analysis :

$$\begin{aligned} X_1' - S_T &= \alpha_1(\text{small bus flow rate}) + \alpha_2(\text{large bus flow rate}) \\ &\quad + \alpha_3(\text{small truck flow rate}) + \alpha_4(\text{large truck flow rate}) \qquad (6) \end{aligned}$$

where S_T = the number of passenger cars that pass through during measurement period or duration of measurement/saturation headway
X_1' = PCUs revised by saturation headway
αi = PCE value.

4. DATA COLLECTION AND REDUCTION

4.1. Data Collection

The survey was performed at 4-leg signalized intersections with level grade, which have at least 3 lanes by each direction. And the intersections that were operated by the central controlled system was preferentially selected to get the signal timing data efficiently. The lane width and grade survey were required as the basic information for the purpose of this research. With geometric data, the headway on queued position with respect to the vehicle type was needed to achieve saturation flow rate, saturation queue position, and to estimate PCEs. The first step of data collection was to understand and identify the characteristics of existing signalized intersections and the second step was to select the suitable survey sites and video recording position.

4.2. Survey Sites

Measuring the ideal saturation flow rate needs potential requisite conditions in traffic and roadway. Following conditions are considered to investigate the saturation flows :

- The traffic of approaches into intersection has less impact on geometric condition. That is, approach lanes are straightforward to intersection and grade is 0%.
- Lane width should be over 3.0m.
- Location that has a relatively higher demand flow, but turbulence by turning movements should not be existed in survey site.
- No friction caused by bus and parking blockage.

. No heavy vehicle included. Passenger cars only.
. Video camera should be located at good point near intersection.

For the basis of above conditions seven sites located in Seoul were selected for data collection. Table 1 shows the roadway and operation conditions of the seven investigated sites.

< Table 1 > Survey sites for ideal saturation flow rate

no.	city	intersection	no. of lanes	surveyed lane	lane width(m)	max. veh. in queue	signal	
							cycle(sec)	green(sec)
1	Seoul	Jongro 3ga WB	4	1st	3.0	15	90-140	53-83
2	"	Kwanghwamun WB	4	1st	3.0	24	90-140	43-70
3	"	Seongmo Hospital WB	5	3rd	3.1	18	80-130	24-33
4	"	Kwangkyo EB	5	2nd	3.2	12	90-140	39-73
5	"	Yoksam SB	6	3rd	3.2	21	100-140	38-52
6	"	Seongmo Hospital WB	5	2nd	3.2	18	120-130	31-33
7	"	Seongsoo Bridge NB	4	2nd	3.2	17	80-130	21-35

Table 2 describes roadway conditions about the six selected survey sites for passenger car equivalent estimation. Along with the site survey to collect data for saturation headway, following conditions were considered as suitable ones to determine PCEs :

. Higher demand flow rate
. Long cycle length
. Proportion of heavy vehicle in traffic is relatively large
. Level grade
. No bus and parking blockage
. Lane width over 3.0m.

< Table 2 > Survey sites for PCEs

no	city	intersection	no. of lanes	surveyed lane	lane width(m)
1	Pusan	Daeyon WB	4	3rd	3.0
2	"	Hadan SB	4	2nd	3.2
3	Seoul	Samsung SB	7	5th	3.0
4	"	Seongmo Hospital WB	5	4th	3.1
5	"	Yoksam SB	6	5th	3.0
6	"	Seongsoo Bridge NB	4	4th	3.1

4.3. Data Reduction

Data was automatically recorded in videotapes and keypunched to micro computers for easier implementation. Headway are analyzed by the rear wheel cross stop line of each vehicle. Collected data was reduced by computer program and appeared in tabular and graphic form to interpret the characteristics of vehicle discharge such as stop line crossing time, vehicle type, queue length, etc. In addition, several specific softwares such as SAS, STATGRAPH, LOTUS, etc. were employed for the statistical analysis.

5. ANALYSIS RESULTS

5.1. Ideal Saturation Flow Rate

1) Distribution of Headway

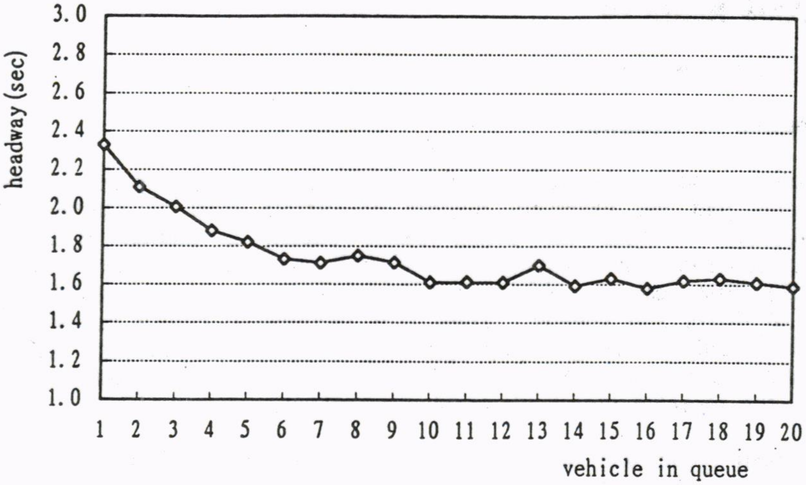
The saturation headway is achieved if only a stable moving queue is established. This assumes that the necessary number of vehicle exist to estabilish a stable moving platoon. When the actual traffic stream is started at a signalized intersection, however, the discharge rate of each successive vehicle is not constant, although the first several vehicles discharge already. It is caused by diverse characters of driver and vehicle. Thus, it is required to collect enough field data, and statistical analyses are generally applied to establish and average traffic pattern. That is, distribution and mean value of headway on the queued position are decided by the repeated investigations at same site.

Well calibrated parameters through the use of regression analysis models are used to characterize traffic flow. For the determination of the ideal saturation flow rate, lane width of 3.2m was decided as condition, since 3.2m is typical value of lane width in Korea and the survey result of headway was relatively uniformly distributed as compared to distributions in case of 3.0m and 3.1m lane widths.

Average headway and accumulated time of vehicle passing the stop line on the queue position are tabulated in Table 3. Figure 1 describes the distribution of headway in graphic form. As shown in Figure 1, even though the headway is not constant, it shows relatively straight trend after several vehicles are discharged.

< Table 3 > Average headways by queue position

queue position	no. of data	avg. headway	variance	min value	max value	stop line crossing time
1	455	2.3274	1.09	0.50	5.32	2.3274
2	461	2.1092	0.62	0.93	3.95	4.4366
3	460	2.0058	0.47	0.99	3.30	6.4424
4	459	1.8795	0.48	0.98	3.30	8.3219
5	458	1.8216	0.44	0.88	2.97	10.1435
6	459	1.7297	0.42	0.98	2.97	11.8732
7	459	1.7117	0.42	0.93	2.80	13.5849
8	457	1.7491	0.46	0.82	3.08	15.3340
9	437	1.7128	0.45	0.87	2.97	17.0468
10	406	1.6100	0.35	0.88	2.80	18.6568
11	379	1.6124	0.35	0.93	2.75	20.2692
12	347	1.6100	0.35	0.88	2.80	21.8792
13	320	1.6994	0.37	0.93	3.18	23.5786
14	295	1.5915	0.31	0.82	2.80	25.1701
15	266	1.6297	0.30	0.82	2.75	26.7998
16	197	1.5787	0.28	0.77	2.97	28.3758
17	118	1.6187	0.22	0.94	2.85	29.9972
18	71	1.6303	0.20	0.77	3.02	31.6275
19	39	1.6097	0.13	1.04	2.69	33.2372
20	28	1.5900	0.13	0.88	2.75	34.8272
21	22	1.5305	0.11	0.88	3.13	36.3575



< Fig. 1 > Average headway distribution

2) Saturation Queue Position

Table 4 illustrates the analysis results of Duncan's test for 4 survey sites with 3.2m of lane width. There are some differences in the saturation queue position in accordance with the confidence interval and survey site. However, headways 6 through 21 are used as reflecting saturated conditions in case of testing all observed headways. Therefore, it would be reasonable to determine the 6th vehicle in queue as the first saturated queue position in engineering and statistical aspects. Table 5 shows the comparison of the various proposed saturation queue position.

< Table 4 > Duncan's test results

location	confidence	queue position						
		group A	group B	group C	group D	group E	group F	group G
Seongsoo Br.	99%	1	2	3-4	5-15	5-16	6-16	17
	95%	1	2	3-4	4,7	5-16	17	
	90%	1	2-4	3.4,7	5-16	11,17		
Yoksam	99%	3,4,7	4-18	5-18	5-20	21		
	95%	3-8	4-19	5-20	21			
	90%	3-1	4-20	11-21				
Kwangkyo	99%	1	2	3	4-9	6-12		
	95%	1-2	2-3	3,5	4-9	4-12	6-12	
	90%	1-2	2-3	3-5	4-12	4-12		
Seongmo Hosp.	99%	1	2-4	5-9,18	6-13,18	7-18		
	95%	1	2-4	5-9,18	6-15	7-16	7-17	
	90%	1	2-4	3-5	5-13,18	6-18	7-18	7-18
Total	99%	1	2-8	3-15	4-21	5-21		
	95%	1	2-4	3-8	4-15	5-21	6-21	
	90%		2-4	3-8	4-15	5-21	6-21	

< Table 5 > Comparison of saturation queue position

	proposed	USHCM	Greenshields	Leong
vehicle position	6	5	5	4

3) Ideal Saturation Flow Rate

Analysis results of regression models for saturation flows are summarized as Table 6 and Table 7. Based upon the saturation queue position in Duncan's test, the ideal saturation flow rate is estimated as 2210 pcphgpl with the 1.629 saturation headway in linear regression analysis. The estimated variance of saturation flow rate is about 100 pcphgpl, which is much smaller than other countries of 200 to 250 pcphgpl.

By non-linear regression analysis, the saturation headway is 1.6116 and the ideal saturation flow rate is computed as 2230 pcphgpl. However, saturation queue position is estimated as the 11th vehicle in the queue. So, it may be not valid in practical use. Thus, this research presents 2210 pcphgpl as the ideal saturation flow rate and recommends 2200 pcphgpl for the convenience of application. Table 8 illustrates the analysis result of ideal saturation flow rate for each country.

< Table 6 > Saturation flows by linear regression

location	equation T = ax+b	R^2	saturation headway(sec)	saturation flows(pcphgpl)	no. of data
Seongmo Hosp.	1.613x+3.56	0.99	1.613	2231	12
Seongsoo Br.	1.617x+3.24	0.99	1617	2226	16
Yoksam	1.669x+1.70	0.99	1.669	2156	7
Kwangkyo	1.709x+2.31	0.99	1.709	2106	16
Total	1.629x+2.29	0.99	1.629	2210	51

< Table 7 > Saturation flows by non-linear regression

location	equation H=exp(ax+b)+c	saturation queue	saturation headway(sec)	saturation flows(pcphgpl)	no. of data
Seongmo Hosp.	exp(-0.53x+0.80)+1.6284	10	1.6005	2250	12
Seongsoo Br.	exp(-1.13x+1.76)+1.6298	11	1.5874	2268	16
Yoksam	exp(-0.20x+0.79)+1.6192	12	1.6629	2165	7
Kwangkyo	exp(-0.32x+0.18)+1.6373	11	1.6290	2210	16
Total	exp(-0.46x+0.42)+1.6317	11	1.6116	2230	51

< Table 8 > Comparison of ideal saturation flow rates

	proposed (pcphgpl)	USHCM[1)] (pcphgpl)	Australia[2)] (tch)[5)]	Canada[3)] (pcphgpl)	Sweden[4)] (vphg)
ideal sat. flow rates	2,200	1,800	1,850	1,350-1,840	1,700

1) TRB, Highway Capacity Manual, 1985
2) Akcelik, Traffic Signals : Capacity and Timing Analysis, Research Report ARR 123
3) Karl-Lennart Bang, Swedish Capacity Manual, Part 3. Capacity of Signalized Intersections, TRR 677, 1978
4) David Richardson, John Schnablegger, Brice Stephenon, and Stan Teply, Canadian Capacity Guide or Signalized Intersections, 1984
5) tch : through car per hour

5.2. Passenger Car Equivalents

Based upon the deducted field data on 6 locations of Table 2, the modified Branston's regression model was applied for analysis. Test procedure was implemented in lane width of 3.0 to 3.2m, and only vehicles discharged from 6th position in the queue were analyzed. The result of regression analysis is tabulated in Table 9 and the number of samples and t-statistics of estimated parameters are shown in Table 10

< Table 9 > Analysis results of PCEs

location		small bus	large bus	small truck	large truck	R^2
Pusan	Hadan SB(3.2m)	1.24	1.84	1.14	1.78	0.98
	Daeyon WB(3.0m)	1.40	1.92	1.19	1.86	0.99
Seoul	Seongmo Hospital WB(3.1m)	1.36	1.59	1.11	2.06	0.98
	Samaung Station SB	1.09	2.33	1.49	2.38	0.94
	Yoksam SB	1.23	1.77	1.33	1.59	0.98
	Seongsoo Bridge NB	1.09	2.56	1.20	1.96	0.97
Total		1.23	1.78	1.20	1.98	0.98

<Table 10> t-statistics of estimated parameters

location	no. of data (cycles)	parameter 1 (small bus)		parameter 2 (small truck)		parameter 3 (large bus)		parameter 4 (large truck)	
		t-value	Prop> | t |	t-value	Prop> | t |	t-value	Prop> | t |	t-value	Prop> | t |
Hadan	50	-16.129	0.0001	-16.417	0.0001	-12.093	0.0001	-8.284	0.0001
Daeyon	84	-9.354	0.0001	-18.326	0.0001	-13.849	0.0001	-5.041	0.0001
Seongmo Hospital	67	-13.419	0.0001	-16.040	0.0001	-3.767	0.0001	-10.949	0.0001
Samaung Station	89	-17.999	0.0001	-21.859	0.0001	-5.660	0.0001	-5.574	0.0001
Yoksam	103	-18.536	0.0001	-29.632	0.0001	-12.756	0.0001	-6.979	0.0001
Seongsoo Bridge	100	-20.176	0.0001	-24.577	0.0001	-5.886	0.0001	-8.076	0.0001
total	493	-35.729	0.0001	-50.696	0.0001	-33.467	0.0001	-19.832	0.0001

Table 11 represents the comparison result of PCE values for each country. As shown in this Table, each country adopts different PCE values according to their specific traffic nature. For example, PCE value of 1.5 is applied uniformly in the USHCM while Australia uses the lane type to determine the equivalents. So, in this research, classifying vehicle type into 4 categories for application in estimating capacity was recommended.

< Table 11 > Comparison of PCEs

classification			PCE
proposed	small heavy vehicle		1.2
		small bus	1.2
		small truck	1.2
	large heavy vehicle		1.9
		large bus	1.8
		large truck	2.0
US HCM	heavy vehicle		1.5
Australia	passenger car, van, pick-ups		1.0
	single unit truck		1.5
	multi-unit truck		2.5
	multi-unit truck heavily loaded		3.5
	buses or street cars		1.75
	motor cycles		0.5
Canada	truck		1.25-3.5
	bus		2.0
United Kingdom	small truck		1.5
	hearvy truck		2.3

source) same as Table 8

6. CONCLUSIONS

The saturation flow rate at signalized intersections of city area is surveyed as 2,200pcphgpl, which is a little higher than that of other countries. Two reasons might be considered : (1) Vehicle size is relatively small, (2) Drivers are aggressive becamse of traffic congestion. And PCE values by vehicle type are also analyzed as 1.2 for small buses and trucks, 1.8 for large buses, and 2.0 for large trucks. These PCE values are slightly different among observation sites. It seems to be resulted from the difference of driver behavior which is affected by queue size, green time length, etc.

REFERENCES

a) Journal papers

R. Akcelik (1989) **Traffic Signals, Capacity And Timing Analysis,** Australian Road Research Board.

K. Bang (1978) **Swedish Capacity Manual,** TRR 667.

R. Kimber, M. McDonald, and N. Hounsel (1986) **The Prediction of Saturation Flows for Road Junctions Controlled by Traffic Signals,** TRRL 67.

R. Stokes, V. Stover, and C. Messer, (1986) **Use and Effectiveness of Simple Linear Regression to Estimate Saturation Flows at Signalized Intersection,** TRR 1091.

R. Stokes, V. Stover, and C. Messer (1986) **Saturation Flows of Exclusive Double Left Turn Lanes,** TRR 1091.

R. Stokes (1988) **Comparison of Saturation Flow Rates Signalized Intersection,** ITE 11.

R. Stokes (1989) **Some Factors Affecting Signalized Intersection Capacity,** ITE 1.

S. Teply (1984) **Canadian Capacity Guide.**

J. Zegeer (1986) **Field Validation of Intersection Capacity Factors,** TRR 1091.

b) Other documents

Korea Institute of Construction Technology & The Korea Transport Institute (1992) **Final Report for Highway Capacity Manual Preparation.**

TRB (1965) **Highway Capacity Manual,** Special Report 87.

TRB (1985) **Highway Capacity Manual,** Special Report 209.