Comparative Analysis of Signalized-Intersection Capacity Methods

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The primary objective of this study was the evaluation of eight methods currently available for capacity and traffic-performance analysis at signalized intersections. The eight methods included the U.S. Highway Capacity Manual method, British method, Swedish method, Transportation Research Board (TRB) Circular 212 planning method, TRB Circular 212 operations and design method, Australian method, National Cooperative Highway Research Program (NCHRP) planning method, and NCHRP operations method. The evaluation was based on applying the eight methods to five intersection data sets for which not only input data were available but also field measurements of lane saturation flows, delays, and percentage of vehicles stopped. The five intersections varied from simple geometric designed intersections with pretimed two-phase signals to more complicated intersections with actuated multiphase signals. Cost-related and effectiveness-related criteria were established in order to evaluate the eight methods. The cost-related criteria included time needed to learn the method, input requirements, clarity and completeness of methodology, and time needed to apply the method. The effectiveness-related criteria included degree of disaggregation, capacity-performance outputs, flexibility of use, and accuracy of predictions. The conclusions included the identification of the limitations of the study, significant results, and future research directions. The NCHRP operations method and the Australian method were found to be the most cost-effective methods. The other methods were about equal in their cost-effectiveness. The NCHRP planning method was found to be an acceptable method when level of effort available is limited and only overall intersection evaluation is needed.

Since an intersection is a point that has to serve all approaches in turn on a highway network, generally the capacities of intersections determine the capacities of a highway network. In order to increase the safety and the capacity of intersections, signals have been used since the 1920s (1). The first U.S. Highway Capacity Manual (HCM) in 1950 contained a chapter for estimating the capacities of signalized intersections (2). Numerous studies have been undertaken to evaluate the different aspects of signalized intersections, and many capacity methods have been developed. Each method corresponds to certain conditions. There is a need for a comparative evaluation to determine which methods should be chosen to evaluate a certain aspect of a signalized intersection. Therefore, a study was designed to apply the eight most accepted methods for capacity analysis to five comprehensive intersection data sets in order to draw conclusions about the eight methods.

A literature search was undertaken and resulted in the identification of eight leading methods for the capacity analysis of signalized intersections. These methods are

1. U.S. HCM method [1965 (3)],
2. British method [1966 (4,5)],
3. Swedish method [1977 (6,7)],
4. Transportation Research Board (TRB) Circular 212 planning method [1980 (8)],
5. TRB Circular 212 operations and design method [1980 (8)],
6. Australian method [1981 (9)],
7. National Cooperative Highway Research Program (NCHRP) planning method [1982 (10)], and
8. NCHRP operations method [1982 (10)].

The next step in the research was to make a comparative analysis of the eight methods in which their input requirements and output options were considered. Inputs were classified as approach width, approach volume, exclusive left- or right-turn lane and length of this lane, percentage of heavy vehicles, number of local buses, parking conditions, peak-hour factor, pedestrians, and several others. Outputs were classified as saturation flow, capacity, delay, percentage of stopped vehicles, queue length, degree of saturation, level of service (LOS), signal timing, and several others. This analysis and a classification scheme of the methods are given next.

The third task was to obtain intersection data sets that included all input data requirements for all eight methods as well as selected traffic-performance measurements that could be compared with the predictions of the various methods. Five intersections were selected from an NCHRP study; all five intersections were located in the San Francisco Bay Area. They included simple geometric designed intersections with two phases and extended into more complicated actuated intersections with multiphases.

The fourth task was to apply the eight methods to the five intersection data sets. Each method was carefully studied in terms of clarity of use, technical completeness, and time requirements for learning and applying the method.

The fifth task was the comparative analysis and evaluation of the eight methods. The criteria for evaluation consisted of input requirements, output flexibility, accuracy of results, and level of effort.

INPUT REQUIREMENTS AND OUTPUT OPTIONS

Input requirements and output options are a mixed blessing. On the one hand, higher levels of input or output generally require more data collection and preparation, more complicated analytical procedures, and greater time required to learn and use the method. On the other hand, lower levels of input or output generally limit the breadth of application, degree of accuracy, and flexibility of output. Hence users must carefully select that method that meets their desired objectives at minimum cost. This discussion is included to aid users by providing a comparative analysis of input requirements and output options of the various methods. Input requirements and output options are summarized in two tables and explained in the next two sections. A classification scheme of the methods is developed and is discussed in the third section.

Input Requirements

The input requirements of each of the methods were reviewed and are summarized in Table 1. The following paragraphs describe the contents of Table 1 under three subcategories: supply inputs, demand inputs, and control inputs.

Supply inputs consist of geometric dimensions, lane configurations, street alignment, bus-stop location, parking, and site characteristics. The only supply input required by all methods is the presence of turning lanes and the permitted movements by lane. The two TRB Circular 212 methods and the NCHRP planning method require little additional supply input. On the other hand, the other five methods require considerably more supply, particularly the NCHRP operations method.

Table 1. Input requirements of eight methods.

	Method							
				TRB Circular 212			NCHRP	
Input Requirement	U.S. HCM	British	Swedish	Planning	Operations and Design	Australian	Planning	Operations
Supply input								
Geometric dimension								
Approach width	X	X	X		X	X		X
Lane width			X		X	X		X
Turning-lane length			X			X		X
Distance to parking		X	X			X		X
Lane configuration								
No. of lanes			X	X	X	X	X	X
Turning lanes	X	X	X	X	X	X	X	X
Permitted movements	X	X	X	X	X	X	X	X
Street alignment								
Horizontal		X						
Vertical		X	X			X		X
Bus-stop location	X							X
Parking								
Presence	X	X				X		X
Turnover								X
Site characteristic								
Population	X							
Location	X	X				X		X
Demand input								
Approach volume								
Through	X	X	X	X	X	X	X	X
Right-turn	X	X	X	X	X	X	X	X
Left-turn	X	X	X	X	X	X	X	X
Vehicle classification								
Truck	X	X	X		X	X		X
Bus	X	X	X					X
Motorcycle or bicycle		X	X					
Traffic pattern								
Peak-hour factor	X				X			X
Arrival platoon								X
No. of local buses	X				X			X
Pedestrian volume			X		X	X		X
Control input								
Signal-timing plan								
Cycle length	X	X	X	X	X	X	X	X
No. of phases	X	X	X	X	X	X	X	X
Duration of phases	X	X	X	X	X	X	X	X
Other signal information								
Pedestrian time			X					X
Pedestrian pushbutton								X

Note: X indicates maximum input. Some methods do not require some inputs.

Demand inputs consist of approach volumes, vehicle classifications, number of local buses, pedestrian volumes, and traffic patterns. The only demand input required by all methods is the approach volume. The TRB Circular 212 planning method and the NCHRP planning method require no additional demand input data. On the other hand, the other six methods require considerably more demand input, particularly the NCHRP operations method.

Control inputs include the signal-timing plan and other signal information. In most methods the signal-timing-plan input is optional. That is, the signal-timing-plan data can be used in the method if provided or can be determined by the method if all other input data are provided except for the signal-timing plans. This option is most readily available in the British, Swedish, Australian, and NCHRP operations methods.

In summary, the TRB Circular 212 planning method and the NCHRP planning method require the least input, whereas the NCHRP operations method requires the greatest amount of input. It should be noted that some of the methods that require the greatest amount of input have incorporated default values when selected input data are not available.

Output Options

The output options of the methods were reviewed and are summarized in Table 2. The following paragraphs describe the output options of the various methods on a comparative basis.

The upper portion of Table 2 provides a comparison between the methods in terms of disaggregation of analysis: lane, lane group, approach, and total intersection. The TRB Circular 212 planning method, the TRB Circular 212 operations and design method, and the NCHRP planning method analyze the total intersection in an aggregate form. At the other extreme in output flexibility, the NCHRP operations method permits the analysis to be made on an individual-lane basis and then provides for aggregation of results on a lane-group, approach, and intersection basis. The HCM method and the British method perform their analyses on an approach and/or turning-lane basis. The Swedish and Australian methods perform their analyses on an individual-lane basis, which could be but is not formally aggregated.

The major outputs of most methods are capacity related and performance related. The TRB Circular 212 planning method, the TRB Circular 212 operations and design method, and the NCHRP planning method do not provide any capacity-related or direct performance outputs. All other methods provide for capacity-related outputs and (with the exception of the HCM method, which provides load-factor information) vehicle-performance-related measures such as delay, percentage of stopped vehicles, and queue

Table 2. Output options of eight methods.

	Method							
				TRB Circular 212			NCHRP	
Output Option	U.S. HCM	British	Swedish	Planning	Operations and Design	Australian	Planning	Operations
Degree of disaggregation								
Lane	X[a]	X[a]	X			X		X
Lane group								X
Approach	X	X						X
Total intersection				X	X		X	X
Capacity-related								
Saturation flow	X	X	X			X		X
Capacity	X	X	X			X		X
Vehicle-performance-related								
Avg delay		X	X			X		X
Percentage of stopped vehicles		X	X			X		X
Queue length		X	X			X		X
Load factor	X							
Pedestrian-performance-related								
Delay						X		
No. stopped						X		
LOS	X			X	X		X	X
Preliminary design	X	X	X	X	X	X	X	X
Improved signal timing								
Cycle length		X	X			X		X
No. of phases						X	X	X
Duration of phases		X	X			X		X
G/C ratio	X	X			X	X		X

[a]Turn lanes only.

length. The Australian method also provides pedestrian performance output.

All U.S. methods provide for an LOS determination and all methods provide for some preliminary design evaluation. The British, Swedish, Australian, and NCHRP operations methods provide for signal-timing determination with the capacity-performance analysis.

Classification of Methods

A review of the last two sections shows that these eight methods fall into a classification scheme that consists of three groups of methods determined by their input requirements and output options. The first group is called the most comprehensive group and consists of the British method, the Swedish method, the Australian method, and the NCHRP operations method. These methods require extensive inputs and analysis time but result in wide and extensive output information. Group 2 is intermediate according to work, input requirements, and output options and consists of the HCM method and the TRB Circular 212 operations and design method. The third group includes the least-complicated methods, which require the least input and working time, and consists of the TRB Circular 212 planning method and the NCHRP planning method. These methods can be used for a very fast overview investigation of the performance of intersections. The variety of comprehensiveness between methods complicates the comparative analysis by considering both the cost and the effectiveness and by restricting the appropriate method selected by the method's dependence on application, input data availability, and output requirements. These issues will be addressed later.

INTERSECTION DATA SETS

The next task of the study was to obtain intersection data sets that included all input data requirements for all eight methods as well as selected traffic-performance measurements that could be compared with the predictions of the various methods. Five such data sets were obtained from an NCHRP study. These particular intersection data sets were selected by considering completeness of field measurements, variety of design and control features, and proximity to the San Francisco Bay Area.

The location and characteristics of these five intersections and their input and traffic-performance measurements will be presented and described in the following two sections.

Location and Characteristics of Intersections

The first intersection is located in Berkeley, California, at Sacramento and Dwight. Sacramento is a divided north-south major arterial with two through lanes in each direction plus an exclusive left-turn lane. Dwight is an undivided east-west collector-type street with one lane in each direction. The intersection is located in a residential area and some distance from adjacent signalized intersections. The signal is a two-phase pretimed controlled signal with a 70-s cycle. The traffic flows are generally light and the percentage of trucks is of the order of 1-2 percent. Parallel parking is permitted on all approaches and near-side bus stops occur on the Sacramento approaches with a far-side bus stop eastbound on Dwight.

The second intersection is located in Berkeley, California, at San Pablo and University. San Pablo is a divided north-south major arterial with two through lanes and an exclusive left-turn lane in each direction. University is a divided east-west major arterial with two through lanes and an exclusive right-turn lane (left-turning movements are prohibited). The intersection is located in an outlying business district and adjacent signalized intersections are approximately 0.25 mile away with an average level of coordination. The signal is a two-phase pretimed controlled signal with a 65-s cycle. The traffic flow is moderately heavy--4-6 percent trucks. Parallel parking and near-side bus stops are located on all approaches.

The third intersection is located in El Cerrito, California, at Carlson and Central. Carlson is a north-south major arterial with two through lanes and an exclusive left-turn lane in each direction. Central is an east-west major arterial with two through lanes in each direction. The intersection is located in an urban fringe area and has little signal coordination with adjacent signals. The signal is a three-phase pretimed controlled signal with an 80-s cycle (the third phase is for exclusive left-turn movements from Carlson). The traffic flow is moderately heavy--1-3 percent trucks. Parking is not permitted on any of the approaches and near-side bus stops exist on the eastbound and southbound approaches.

The fourth intersection is located in Richmond, California, at San Pablo and McDonald. San Pablo is a divided north-south major arterial with two through lanes and with exclusive left-turn and right-turn lanes. McDonald is an east-west major arterial with one through lane and with an exclusive left-turn lane in each direction (in addition, eastbound McDonald has an exclusive right-turn lane). The intersection is located in an outlying business district and there are no nearby adjacent signals. The signal is a six-phase fully actuated controlled signal with a maximum 95-s cycle. The sequence of phasing is eastbound (all movements), westbound (all movements), northbound and southbound left-turn movements only, continued northbound or southbound left-turn movement with adjacent through and right-turn movement, and finally the through- and right-turn movements only on San Pablo. The traffic flow is very heavy with 0-2 percent trucks. Parking is not permitted on any approach and the only bus stop (near side) is located on the eastbound approach.

The fifth and last intersection is located in Berkeley, California, at Grove and Rose. Grove is a north-south collector-type street with a single-lane approach in each direction. Rose is an east-west collector-type street with a single-lane approach in each direction. The intersection is located in an urban fringe area with no nearby adjacent signals. The signal is a two-phase pretimed controlled signal with a 65-s cycle. The traffic flow is generally light--1-5 percent trucks. Parking is permitted on all approaches and there are far-side bus stops on Grove.

In summary, these five intersections have some common features and at the same time each has some unique features. All intersections are located in flat topography, have four approaches, provide for two-way operations on all crossing streets, and have less than 6 percent truck traffic. The unique features of the intersection at Sacramento and Dwight are that two approaches have only single lanes and the traffic flow is generally light. The intersection at San Pablo and University has fairly heavy pedestrian and local bus activities and special turn features (no left turns on two approaches and an exclusive right-turn lane). The intersection at Carlson and Central has a three-phase pretimed signal controller and parking is not permitted on any of the approaches. The intersection at San Pablo and McDonald has a six-phase fully actuated signal controller and operates under very heavy traffic conditions. The intersection at Grove and Rose has only single-lane approaches with relatively heavy pedestrian activities.

Input and Traffic-Performance Measurements

The field measurements that are necessary in order to apply the eight methods to the five intersections are given in Table 3. Not all input measurements were required in all of the eight methods.

Selected traffic-performance measurements were taken for selected lane groups at the five intersections. These field measurements consisted of saturation flow, average delay, and percentage of vehicles stopped. These measurements are presented in Figures 1-3.

NUMERICAL RESULTS

The eight methods were then applied to the five intersection data sets. This application process provided three different ways of evaluating and comparing the eight methods. First, the application provided insights as to the clarity and the completeness of the methods. Evaluation of clarity and completeness of the methods will be discussed later.

Second, the application provided estimates of time requirements to learn and apply each method. These time-requirement estimates are presented in Table 4 for comparative purposes and not as absolute values. As noted from the table, time needed to learn and apply the methods varied considerably.

Finally, the application provided traffic-performance predictions that could be compared with field-measured traffic performances. These comparisons included saturation flow, average total delay, percentage of vehicles stopped, and LOS and will be presented and discussed in the following four paragraphs.

Five of the eight methods predict saturation flow. Measured saturation flow and directly comparable predicted saturation flow for the five methods were available for 13 lane groups. These saturated flows are presented in tabular form in Figure 1. The intersection number, direction of movement, and permitted traffic movements are identified for each lane group. Then the lane saturation flows for each of the five methods are presented as well as the measured values. The mean value and standard deviation are given for each column.

Four of the eight methods predict average total delay. Measured delay and directly comparable predicted delay for the four methods were available for 30 lane groups. These average total delays are presented in tabular form in Figure 2. The individual lane groups are identified and average total delays entered for each method. The mean value and standard deviation are given for each column.

Four of the eight methods predict percentage of vehicles stopped. Measured percentage of vehicles stopped and directly comparable predicted percentage of vehicles stopped for the four methods were available for 30 lane groups. These data are presented in tabular form in Figure 3. The individual lane groups are identified and the percentage of vehicles stopped is entered for each method. The mean value and standard deviation are given for each column.

Three of the methods could not be included in the saturation-flow evaluation and four of the methods could not be included in the evaluation of average total delay or percentage of vehicles stopped. In order to provide some form of comparison for these methods, an LOS analysis was performed. The measured LOS was based on measured average total delay and converted to the LOS scale based on the NCHRP operations method scale relationship. All five U.S. methods provided LOS predictions. These LOS indicators are presented in tabular form in Figure 4 for 30 lane groups. The individual lane groups are identified and LOS is entered for each method. Different methods provided different levels of aggregation of LOS as indicated in Figure 4.

COMPARATIVE ANALYSIS AND EVALUATION

The comparative analysis and evaluation of the eight methods are discussed in this section. The criteria selected for evaluation included level of effort required and quantitative or qualitative effective-

Table 3. Input measurements of five selected intersections.

	Sacramento-Dwight (Berkeley)				San Pablo-University (Berkeley)				Carlson-Central (El Cerrito)			
Input[a]	NB	SB	EB	WB	NB	SB	EB	WB	NB	SB	EB	WB
Approach width (ft)	45	45	17	21	39	39	31	32	34	34	22	28
No. of through lanes	2	2	1	1	2	2	2	2	2	2	2	2
No. of right-turning lanes	0	0	0	0	0	0	1	1	0	0	0	0
No. of left-turning lanes	1	1	0	0	1	1	0	0	1	1	0	0
Length, turning lane (ft)	110	110	-	-	170	165	-	-	150	100	-	-
Right-turning radii (ft)	10	10	10	10	10	10	10	10	15	10	40	20
Left-turning radii	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Gradient of approach	0	0	0	0	0	0	0	0	0	0	0	0
Peak-hour factor	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Bus-stop location	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N
Site characteristic	Residential				Outlying business				Fringe			
Parking condition	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N
Parking distance to stop line (ft)	110	72	65	60	90	90	140	140	165	-	-	-
Approach volume	720	620	440	390	420	480	820	850	680	260	800	360
Load factor	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Right-turning volume	50	40	50	18	65	52	13	120	40	37	200	74
Left-turning volume	84	125	55	47	73	81	-	-	210	59	78	16
Heavy vehicles (%)	1	1	2	1	6	3	4	4	1	1	2	1
No. of local buses	11	0	0	0	8	7	8	13	0	1	7	0
Bicycles or motorcycles (%)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pedestrian volume	0	0	9	51	57	84	7	45	1	5	0	7
No. of parking maneuvers	1	1	1	1	3	1	3	3	-	-	-	-
Arrival type	3	3	3	3	3	3	4	4	4	3	3	3
Signal timing[b]	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt
No. of phases	2	2	2	2	2	2	2	2	3	3	3	3
Pedestrian walking time (s)	11	9	22	22	16	16	17	17	19	14	17	17

Note: Y = yes; N = no; NA = not available.

[a]These parameters are those required by the NCHRP method (10).

[b]Pt = pretimed; Act = fully actuated.

ness. These two criteria were applied to the eight methods and the comparative analysis and evaluation are presented in the following two subsections.

Level of Effort Required

Time needed to learn the method, input requirements, clarity and completeness of methodology, and time needed to apply the method were used to assess the level of effort required. This evaluation resulted in the classification of the eight methods into three groups.

The first group, the one requiring the least level of effort, consisted of the TRB Circular 212 planning method and the NCHRP planning method. These two methods required only 1-2 h in order to learn the method and only 0.5 h to typically apply the method. These two methods required much less input data than the other six methods. The experience from this study indicated that step-by-step procedures and sample problems are slightly clearer in the NCHRP planning method than in the previous TRB Circular 212 planning method.

The second group, the one requiring a moderate level of effort, consisted of the HCM method and the TRB Circular 212 operations and design method. These two methods required 2-4 h in order to learn the method and approximately 1 h to typically apply the method. These two methods required a moderate amount of input data and are about equal in terms of clarity and quality of sample problems.

The third and last group consisted of the four methods that require the greatest level of effort. These were the British, the Swedish, the Australian, and the NCHRP operations methods. These methods required 8-20 h to learn and typically required 1-4 h per application. Input requirements were rather significant; they varied from the British method, which required the least in this group, to the NCHRP operations method, which required the greatest amount of input data. Several of the methods, notably the NCHRP operations method, provided default values when certain input data are not available. Of these four methods, the NCHRP operations method is the most user-oriented; it uses clear step-by-step procedures and numerical examples.

Quantitative or Qualitative Effectiveness

Degree of disaggregation, capacity-performance outputs, flexibility of use, and accuracy of predictions were used as criteria in assessing the quantitative or qualitative effectiveness of the eight methods. It was more difficult to classify the eight methods into groups based on criteria of quantitative or qualitative effectiveness. Instead, the methods will be evaluated for each criterion individually in the following four paragraphs.

The criterion of degree of disaggregation provided a clear differentiation between methods. The two TRB Circular 212 methods and the NCHRP planning method are the most aggregated in that results are provided only for the total intersection. The next level of disaggregation was provided by the HCM method and the British method on an intersection-approach basis and for special turn lanes. The Swedish and the Australian methods provide analysis on an individual-lane basis. The greatest degree of flexibility in degree of disaggregation is provided in the NCHRP operations method, in which the user may perform analysis by individual lane, lane group, approach, and/or total intersection.

The criterion of capacity-performance output applied to the eight methods provided a three-level classification. The two TRB Circular 212 methods and the NCHRP planning method provided the least output; only the overall LOS was specified. The HCM method provided saturation-flow and capacity values but the only performance values were load factor and LOS. The other four methods (British, Swedish, Australian, and NCHRP operations methods) provided saturation flow, capacity, delay, percentage of stopped vehicles, and queue-length outputs. In addition, the Australian method provided pedestrian-performance outputs.

The criterion of flexibility of use included LOS,

San Pablo-McDonald (Richmond)				Grove-Rose (Berkeley)			
NB	SB	EB	WB	NB	SB	EB	WB
44	43	39	23	20	20	18	20
2	2	1	1	1	1	1	1
1	1	1	0	0	0	0	0
1	1	1	1	0	0	0	0
300	160	250	110	-	-	-	-
10	40	20	40	10	10	10	10
NA	NA	NA	NA	NA	NA	NA	NA
0	0	0	0	0	0	0	0
0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
N	N	Y	N	Y	Y	N	N
Outlying business				Fringe			
N	N	N	N	Y	Y	Y	Y
-	-	-	-	5	18	37	16
1210	560	790	300	350	450	150	170
NA	NA	NA	NA	NA	NA	NA	NA
95	78	260	56	60	20	31	21
210	108	320	113	18	23	30	39
2	1	1	0	4	1	5	1
0	0	4	0	3	3	0	0
NA	NA	NA	NA	NA	NA	NA	NA
13	4	0	11	51	56	4	79
-	-	-	-	4	4	2	0
3	3	3	3	5	3	3	2
Act	Act	Act	Act	Pt	Pt	Pt	Pt
6	6	6	6	2	2	2	2
12	16	21	18	10	9	13	10

Figure 1. Results for lane saturation flow.

LOCATION			LANE SATURATION FLOWS (VPH OF GREEN)					
				PREDICTED METHOD				
INTERSECTION NUMBER	DIRECTION OF MOVEMENT	TRAFFIC MOVEMENTS	MEASURED	HCM	BRITISH	SWEDISH	AUSTRALIAN	NCHRP
1	EB	↖↑↗	1494	1234	1898	1820	1498	1604
1	WB	↖↑↗	1457	1411	2367	1360	1530	1680
3	NB	↖	1636	1248	1620	1670	1810	1573
3	EB	↖↑↑↗	1386	1430	1532	1770	1596	1647
4	NB	↖	1446	1360	1638	1650	1793	1484
4	NB	↑↑↗	1626	1300	2078	1810	1814	1673
4	SB	↑↑	1660	1278	2101	1800	1775	1631
4	EB	↖↑	1446	1679	1886	1830	1775	1476
4	WB	↑↗	1837	1714	2470	1860	1614	1614
5	NB	↖↑↗	1104	1480	2132	1630	1348	1353
5	SB	↖↑↗	1475	1802	1775	1880	1429	1401
5	EB	↖↑↗	1286	1012	1805	1160	1284	1270
5	WB	↖↑↗	1525	1157	1488	1760	1219	1373
MEAN			1490.6	1392.7	1906.9	1692.3	1575.8	1521.5
STD. DEVIATION			181.9	229.4	308.9	211.1	211.0	137.1

Figure 2. Results for average total delay.

LOCATION			AVERAGE TOTAL DELAY (SECS/VEH)				
				PREDICTED METHODS			
INTERSECTION NUMBER	DIRECTION OF MOVEMENT	TRAFFIC MOVEMENT	MEASURED	BRITISH	SWEDISH	AUSTRALIAN	NCHRP
1	NB	↖	11	12	12	10	32
1	NB	↑↑↗	10	9	13	11	11
1	SB	↖	15	9	11	9	31
1	SB	↑↑↗	7	9	11	10	10
1	EB	↖↑↗	29	12	27	19	42
1	WB	↖↑↗	39	14	24	18	37
2	NB	↖	22	11	13	13	40
2	NB	↑↑↗	16	12	13	13	13
2	SB	↖	14	11	13	13	40
2	SB	↑↑↗	9	12	13	14	13
2	EB	↑↑↗↗	22	15	19	15	11
2	WB	↑↑↗↗	6	13	20	14	14
3	NB	↖	32	25	30	28	35
3	NB	↑↑↗	21	20	22	25	18
3	SB	↖	28	24	24	25	42
3	SB	↑↑↗	25	18	19	20	21
3	EB	↖↑↑↗	34	18	24	21	29
3	WB	↖↑↑↗	17	17	18	18	29
4	NB	↖	41	32	31	35	56
4	NB	↑↑↗↗	39	23	22	28	27
4	SB	↖	40	43	17	42	66
4	SB	↑↑↗	31	28	15	33	33
4	EB	↖	47	63	30	34	59
4	EB	↖↑↗	77	37	35	35	38
4	WB	↖	40	37	23	37	71
4	WB	↑↗	49	38	35	39	36
5	NB	↖↑↗	3	5	6	6	7
5	SB	↖↑↗	4	5	5	6	12
5	EB	↖↑↗	47	21	26	22	43
5	WB	↖↑↗	19	19	21	21	53
MEAN			26.5	20.4	19.7	21.1	32.3
STD. DEVIATION			16.8	13.0	8.0	10.4	17.4

Figure 3. Results for percentage of vehicles stopped.

LOCATION			VEHICLE STOPPING (PERCENT)				
				PREDICTED METHOD			
INTERSECTION NUMBER	DIRECTION OF MOVEMENT	TRAFFIC MOVEMENT	MEASURED	BRITISH	SWEDISH	AUSTRALIAN	NCHRP
1	NB	↖	80	62	56	51	68
1	NB	↑↑↗	47	53	55	55	46
1	SB	↖	54	52	56	55	66
1	SB	↑↑↗	29	52	55	52	45
1	EB	↖↑↗	43	74	70	77	78
1	WB	↖↑↗	70	70	68	73	74
2	NB	↖	86	59	64	59	77
2	NB	↑↑↗	40	63	63	60	51
2	SB	↖	56	59	64	60	77
2	SB	↑↑↗	38	64	63	60	51
2	EB	↑↑↗↗	35	74	68	66	48
2	WB	↑↑↗↗	17	67	69	68	54
3	NB	↖	65	87	83	80	74
3	NB	↑↑↗	75	78	74	72	58
3	SB	↖	75	79	78	72	78
3	SB	↑↑↗	71	72	71	66	62
3	EB	↖↑↑↗	61	83	70	74	69
3	WB	↖↑↑↗	56	71	68	65	69
4	NB	↖	78	93	79	82	84
4	NB	↑↑↗↗	65	79	72	78	68
4	SB	↖	94	97	83	86	88
4	SB	↑↑↗	58	80	69	79	72
4	EB	↖	84	96	83	82	87
4	EB	↖↑↗	84	91	85	83	75
4	WB	↖	83	90	86	81	90
4	WB	↑↗	87	93	89	86	75
5	NB	↖↑↗	20	41	37	43	36
5	SB	↖↑↗	22	44	37	46	50
5	EB	↖↑↗	85	81	76	78	79
5	WB	↖↑↗	58	83	76	77	84
MEAN			60.5	73.0	69.0	68.9	67.8
STD. DEVIATION			22.1	15.7	12.8	12.3	14.5

Table 4. Comparison of level of effort for eight methods.

	Method							
				TRB Circular 212			NCHRP	
Level of Effort	U.S. HCM	British	Swedish	Planning	Operations and Design	Australian	Planning	Operations
Time needed to learn (h)	4	8	20	2	4	20	1	15
Time needed to apply (h)	1	1	4	1/2	1	3	1/2	3

Figure 4. Results for LOS.

LOCATION			LEVEL OF SERVICE					
				PREDICTED METHOD				
					CIRCULAR		NCHRP	
INTERSECTION NUMBER	DIRECTION OF MOVEMENT	TRAFFIC MOVEMENT	MEASURED[b]	HCM	PLANNING	OPERATIONS DESIGN	PLANNING	OPERATIONS
1	NB	↖↑↑↗	A	A	A	B	A[a] (A-C)	B
1	SB	↖↑↑↗	A	A	A	B	"	B
1	EB	↖↑↗	C	E	A	B	"	D
1	WB	↖↑↗	C	B	A	B	"	C
2	NB	↖	B	A	A	A	A[a] (A-C)	D
2	NB	↑↑↗	B	A	A	A	"	B
2	SB	↖	B	A	A	A	"	D
2	SB	↑↑↗	A	A	A	A	"	B
2	EB	↑↑↗↗	B	B	A	A	"	A
2	WB	↑↑↗↗	A	B	A	A	"	A
3	NB	↖	C	D	B	B	A[a] (A-C)	D
3	NB	↑↑↗	B	D	B	B	"	B
3	SB	↖	C	A	B	B	"	D
3	SB	↑↑↗	B	A	B	B	"	B
3	EB	↖↑	C	E	B	B	"	D
3	EB	↑↗	C	E	B	B	A[a] (A-C)	B
3	WB	↖↑	B	A	B	B	"	D
3	WB	↑↗	B	A	B	B	"	B
4	NB	↖	D	E	B	C	C[a] (A-C)	E
4	NB	↑↑↗↗	C	E	B	C	"	C
4	SB	↖	D	C	B	C	"	F
4	SB	↑↑↗	C	C	B	C	"	C
4	EB	↖	D	E	B	C	"	E
4	EB	↖↑↗	E	E	B	C	"	D
4	WB	↖	D	C	B	C	"	E
4	WB	↑↗	D	C	B	C	"	D
5	NB	↖↑↗	A	A	A	A	A[a] (A-C)	A
5	SB	↖↑↗	A	A	A	A	"	A
5	EB	↖↑↗	D	A	A	A	"	D
5	WB	↖↑↗	B	A	A	A	"	D

a) Using the criteria in the "old" report of NCHRP 3-28 Project.

b) Measured values are derived from measured stopped delay values based on the NCHRP 3-28 criteria.

preliminary design, and signal-timing applications. The five U.S. methods all provided LOS results. All eight methods could be used in preliminary design investigations. The major difference between methods was in signal-timing applications. The British and the Swedish methods provided considerable flexibility with signal-timing investigations. However, the Australian and the NCHRP operations methods provided the greatest flexibility with signal timing. The NCHRP operations method was especially user-oriented; it provided step-by-step instructions and accompanying work sheets.

The criterion of accuracy of predictions provided a very quantitative comparison between methods. Not all eight methods provided numerical results that could be compared with the various measurements taken in the field. Therefore, it was necessary to use different measurements to compare different methods. Lane saturation flow was used to compare the HCM, British, Swedish, Australian, and NCHRP operations methods. Percentage of delay and vehicles stopped was used to compare the British, Swedish, Australian, and NCHRP operations methods. LOS was used to compare the five U.S. methods. The comparison between these measurements and predictions will be discussed in the next four paragraphs.

The results for lane saturation flow were presented in Figure 1. The measured and predicted lane saturation flows are shown for 13 lane groups and the calculated mean and standard deviation are indicated at the bottom of the column for each method. In the following analyses, it is assumed that the measured values are correct and any differences between the predicted and measured values are considered to be errors in the predicted methods. Statistical analyses were performed and their results are given in Table 5. The two best prediction methods for lane saturation flows were the NCHRP operations method and the Australian method. However, even these methods had mean errors of the order of 8-12 percent of the mean measured lane saturation flows.

The results for average total delay were presented in Figure 2. The measured and predicted average total delays are shown for 30 lane groups and the calculated mean and standard deviation are indicated at the bottom of the column for each method.

Statistical analyses were performed and their results are shown in Table 5. Average stopped delay was actually measured in the field and predicted by the NCHRP operations method. A factor of 1.3 [based on an earlier Federal Highway Administration (FHWA) study and also reported in the NCHRP study] was applied to the stopped delays in order to compare them with the other methods that are based on total average delay. The best prediction method for total average delay was the Australian method, followed by the British and the Swedish methods. The NCHRP method performed the least effectively and inspection of the regression plots indicated two subgroups of data points: separate left-turn lanes and other lane groups. Further linear-regression analysis of these two subgroups provided the following additional results:

Separate left-turn lanes:

$$d_{obs} = 0.74d_{pred} - 5.95 \quad \text{with } r = 0.91 \tag{1}$$

Other lane groups:

$$d_{obs} = 0.91d_{pred} + 2.48 \quad \text{with } r = 0.82 \tag{2}$$

These results clearly indicate that the major deficiency in predicting total average delay in the NCHRP method lies with separate left-turn lanes.

The results for percentage of vehicles stopped were presented in Figure 3. The measured and predicted percentages of stopped vehicles are shown for 30 lane groups and the calculated mean and standard deviation are indicated at the bottom of the column for each method. Statistical analyses were performed and their results are shown in Table 5. The NCHRP operations method was slightly better than the other three methods, which were about equal. However, all four methods exhibited mean errors of the order of 20-25 percent of the measured mean of percentage of stopped vehicles.

The LOS results were presented in Figure 4. Because of the integer nature of LOS, the comparative analyses were performed in a slightly different manner, as given in Table 6, in which frequencies of differences in LOS between the indicated method and the field results are displayed. For example, if we consider the HCM method, the LOS of 11 of the 30 lane groups was predicted to be one LOS higher than that obtained in the field. The NCHRP operations method predicts slightly lower (worse) LOS than field conditions, whereas the other four methods predict one LOS higher (better) than field conditions. The percentages of the frequencies for each method are tabulated below. Three levels of percentages are given: predicted LOS equals field results, predicted LOS within plus or minus one LOS of field results, and predicted LOS within plus or minus two LOS of field results. The TRB Circular 212 operations and design method and the NCHRP operations method represented field conditions slightly better than the other three methods.

	Method				
		TRB Circular 212		NCHRP	
Level	U.S. HCM	Planning	Operations and Design	Planning	Operations
Predicted equal to field (%)	27	33	33	27	40
Predicted within ±1 LOS of field (%)	77	66	94	74	83
Predicted within ±2 LOS of field (%)	97	93	97	97	100

CONCLUDING REMARKS

This final section contains some concluding remarks about the limitations of the study, significant results, and future research directions.

There were a number of factors that limited the effectiveness of this study. All data sets were obtained at intersections located in the San Francisco Bay Area and did not include locations elsewhere in the United States or abroad. Although the characteristics of the five intersections varied, a greater variety of intersections and traffic characteristics would have enhanced the study. Additional traffic-performance measures such as total delay, load factor, and queue length should have been obtained in the field in order to more fully evaluate prediction methods. Greater precision in the field measurements and more lane groups would have strengthened the statistical analysis and its interpretation. Finally, some of the procedures in some of the methods were not explicit, which caused the users to apply judgment and not always get identical results.

The eight methods were compared on the basis of their cost-effectiveness. The NCHRP operations method and the Australian method were found to be the most cost-effective. The other methods were about equal in their cost-effectiveness.

Table 7 attempts to summarize the most significant results of this comparative study by assessing the level of effort required and quantitative or qualitative effectiveness. In regard to level of effort required, the eight methods were classified into three groups: least effort, moderate effort, and most effort. In regard to quantitative or qualitative effectiveness, the comparisons are more difficult because of the variety of ways effectiveness could be measured and because of strengths and weaknesses in the various methods. The NCHRP operations method and the Australian method were found to be the most effective, followed by the Swedish and British methods. The HCM method was the next most effective, followed by the two TRB Circular 212 methods and the NCHRP planning method. The NCHRP planning method was found to be an acceptable method when level of effort available is limited and only overall intersection evaluation is needed.

Future research should have two major directions. First, this comparative study should be extended to eliminate or at least reduce the previously identified limitations. These include broadening the environments and intersection types, increasing the number of lane groups, including additional field traffic-performance measurements, and providing greater field measurement precision. Second, the two NCHRP methods should be enhanced. Some deficiencies have been identified in this study and it is suggested that user surveys be undertaken to identify other possible difficulties. The major research effort should be directed toward increasing the accuracy and reducing the level of effort required by the NCHRP operations method. Although some improvement in accuracy of predicting lane saturation flow and percentage of stopped vehicles is

Table 5. Statistical analysis of results for lane saturation flow, total average delay, and percentage of stopped vehicles.

	Lane Saturation Flow					
		Prediction Method				
Calculation	Measured	U.S. HCM	British	Swedish	Australian	NCHRP
Overall mean value	1491	1393	1907	1692	1576	1522
Significant difference between measured and predicted means (0.05 level)	-	No	Yes	Yes	No	No
SD	182	229	309	211	211	137
Significant difference between measured and predicted SDs (0.05 level)	-	No	No	No	No	No
Mean error	-	249	424	236	174	117
Root-mean-square error	-	280	526	280	208	147
No. of high estimates	-	4	11	11	9	7
No. of low estimates	-	9	2	2	4	6
Linear regression						
Y-intercept	-	+1333	+1212	+792	+807	+293
Slope	-	+0.113	+0.146	+0.413	+0.434	+0.787
Correlation coefficient (r)	-	0.14	0.25	0.48	0.50	0.59
Significant difference from slope = 1.00	-	Yes	Yes	Yes	Yes	No
Significant difference between r and r = 0	-	No	No	No	No	Yes

Table 6. Analysis of results for LOS.

	Method				
		TRB Circular 212		NCHRP	
LOS Difference	U.S. HCM	Planning	Operations and Design	Planning	Operations
+3	1	2	1	1	0
+2	1	8	1	7	0
+1	11	10	16	14	3
0	8	10	10	8	12
-1	4	0	2	0	10
-2	5	0	0	0	5
-3	0	0	0	0	0

Table 7. Summary of comparative analysis.

	Method							
				TRB Circular 212			NCHRP	
Item	U.S. HCM	British	Swedish	Planning	Operations and Design	Australian	Planning	Operations
Level of effort required	Moderate	Most	Most	Least	Moderate	Most	Least	Most
Quantitative/qualitative effectiveness								
Degree of disaggregation	2	2	3	1	1	3	1	4
Capacity-performance outputs	2	3	3	1	1	4	1	3
Flexibility of use	2	3	3	1	1	4	1	4
Accuracy								
Lane saturation flows	2	2	2	NA	NA	3	NA	4
Total avg delay	NA	3	3	NA	NA	4	NA	2
Percentage of stopped vehicles	NA	2	2	NA	NA	2	NA	3
LOS	2	NA	NA	2	3	NA	2	3

desired, the greatest inaccuracies were in predicting delay. A limited investigation revealed that the magnitude of errors in estimating delay was greatly influenced by type of lane group and especially delays associated with exclusive left-turn lane groups. One of the major objections to the NCHRP operations method is the level of effort required. The primary ways of reducing the level of effort required are through improved use of default values, employment of nomographs, and/or computerization.

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Total Avg Delay					Percentage of Stopped Vehicles				
	Prediction Method					Prediction Method			
Measured	British	Swedish	Australian	NCHRP	Measured	British	Swedish	Australian	NCHRP
26.5	20.4	19.7	21.3	32.3	60.5	73.0	68.9	68.9	67.8
-	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes
16.8	13.0	8.0	10.4	17.4	22.1	15.7	12.8	12.3	14.5
-	No	Yes	Yes	No	-	Yes	Yes	Yes	Yes
-	8.4	9.3	7.6	12.2	-	15.8	12.7	14.2	12.6
-	12.4	12.4	11.6	15.9	-	19.8	16.5	18.7	15.5
-	9	10	11	20	-	25	22	19	21
-	21	20	19	10	-	5	8	11	9
-	+6.5	-8.2	-1.4	+7.3	-	-12.25	-24.46	-18.85	-21.28
-	+0.98	+1.76	+1.32	+0.59	-	+0.998	+1.234	+1.153	+1.207
-	0.76	0.83	0.82	0.61	-	0.70	0.71	0.64	0.79
-	No	Yes	No	Yes	-	No	No	No	No
-	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes

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REFERENCES

1. A.D. May. Intersection Capacity 1974: An Overview. TRB, Special Rept. 153, 1975, pp. 50-59.
2. Highway Capacity Manual. TRB, Washington, DC, 1950.
3. Highway Capacity Manual--1965. TRB, Special Rept. 87, 1965.
4. F.V. Webster. Traffic Signal Settings. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, TRRL Tech. Paper 39, 1958.
5. F.V. Webster and B.M. Cobbe. Traffic Signals. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, TRRL Tech. Paper 56, 1966.
6. B.E. Peterson and E. Imre. Beräkning av kapacitet, kölängd, fördröjning i vägtrafikanläggningar (Swedish Capacity Manual). Statens Vägverk, Stockholm, Sweden, 1977.
7. K.-L. Bang. Capacity of Signalized Intersections. TRB, Transportation Research Record 667, 1978, pp. 11-21.
8. Interim Materials on Highway Capacity. TRB, Transportation Research Circular 212, 1980.
9. R. Akcelik. Traffic Signals: Capacity and Timing Analysis. Australian Road Research Board, ARRB Res. Rept. 123, March 1981.
10. JHK and Associates. Urban Signalized Intersection Capacity. NCHRP [Project 3-28(2)], unpublished, May 1982.

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Speeds and Flows on an Urban Freeway: Some Measurements and a Hypothesis

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Speeds and flows were measured in a bottleneck section of a six-lane urban freeway near Toronto, Canada, on three successive mornings. The average capacity flow was 1984 passenger-car units per lane per hour, very close to the traditional value of 2000, but at an average speed of 80 km/h (49 mph), a much higher speed than is usually indicated in textbooks and manuals. Frequency distributions of the observed flows and speeds at capacity are reported and used as a part of a general discussion of the meaning of the term "capacity." In order to study the relationship between speed and flow, measurements were also made before the section reached capacity. At flows less than three-fourths of capacity, the average speed was 100 km/h (62 mph); there was no apparent decrease in speed as the flow increased. Between three-fourths of capacity and capacity, a gradual reduction in speed from 100 km/h to the 80-km/h speed observed at capacity was expected, but no such smooth speed transition was observed. The nature of the data leads to the hypothesis that the average speed on an urban freeway with a speed limit, where neither grades nor curvature is severe and where the traffic is not affected by downstream bottlenecks, may not vary as a function of flow but may depend only on whether the traffic is or is not a capacity flow discharged from an upstream queue.

A good understanding of the way in which speed varies with flow is an essential prerequisite to the creation and use of any level-of-service concept for freeways. Unfortunately, misinformation about this relationship abounds. In this paper, we present some data and some ideas that we hope will help to combat some of the misinformation. As we studied the data, however, we found ourselves questioning not just the things we had intended to challenge, but also some of the things we ourselves believed. What was intended to be a straightforward presenta-