to those of the equity operations.

In general, minimum total delay operation is more desirable than vehicle priority operation and equity operation because it avoids long pedestrian delays that can result from vehicle priority operation at light vehicle flows and vehicle delays similar to those of vehicle priority operation. And, finally, M_{max} can be chosen to produce acceptable average pedestrian delays at heavy vehicle flows and to alleviate the risk of unstable system performance.

SUMMARY

This paper characterizes the performance of a pedestrian-actuated signal control system in terms of traffic delays, describes the three types of signal operations, and discusses the validity of the assumption that traffic arrives randomly. This was verified by data collected for isolated intersections at Potsdam.

Vehicle priority operation may result in excessive pedestrian delays when long minimum vehicle green durations are chosen. Shorter vehicle greens, on the other hand, risk unstable system performances with respect to vehicle delay. Equity operation is preferable from the viewpoint of pedestrians, but it may bring about unstable system performance when heavy vehicle flows are present. Minimum total delay operation reduces the negative features of the other two operations and is thus more desirable.

Regardless of the types of operation, pedestrian green duration should always be set at its minimum requirement, which is 7 s plus the time needed for a pedestrian to cross the intersection. The setting of minimum vehicle green duration, on the other hand, depends on intersection width and traffic flow. In general, broader intersections and heavier vehicle flows require longer minimum vehicle green duration.

ACKNOWLEDGMENT

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Level of Service at Signalized Intersections

T. C. Sutaria, Rady and Associates, Inc., Fort Worth, Texas
J. J. Haynes, Department of Civil Engineering, University of Texas at Arlington

In the 1965 Highway Capacity Manual levels of service at signalized intersections are related to load factor, which was intuitively judged the best level of service indicator available. Load factor has, however, presented such problems as its insensitivity to low service volume, absence of any rational basis for defining breakpoints, and difficulty in identifying loaded cycle. A rational method for quantifying the different levels of service at signalized intersections was therefore needed. In our research we used a road-user opinion survey that involved depicting and rating different traffic situations at a carefully selected single signalized intersection. Over 300 drivers rated randomly arranged film sequences of two types—a driver's view (microview) and an overall view (macroview) of an intersection—and evaluated these films, segment by segment, in terms of appropriate levels of service. Field studies and the attitude survey provided data for the development of two psychophysical models. Statistical analysis indicated that average individual delay correlated better with level of service rating than with measured load factor and encompassed all levels of service. Of all parameters affecting levels of service, load factor was rated highest by road users.

In the 1965 Highway Capacity Manual (HCM) (1) the concept of level of service was introduced for both uninterrupted flow conditions and street intersections with signalized control. Level of service is "a qualitative measure of the effect of a number of factors, which include speed, travel time, traffic interruptions, freedom to maneuver, safety, driving comfort, convenience and operating costs." There are stops at intersections, so speed cannot be the appropriate measure of level of service; an operational index called load factor (LF), then, was used to determine the various levels of service at signalized intersections. HCM defined this index as a "ratio of the total number of green signal intervals that are fully utilized by traffic during the peak hour to the total number of green intervals, for that approach during the same period." The different levels of service are identified alphabetically from A (free flow) to F (forced flow or stop-and-go conditions), based on the value of LF as follows:

Level of Service	Load Factor	Level of Service	Load Factor
A	0.0	D	0.3 to 0.7
B	0.0 to 0.1	E	0.7 to 1.0
C	0.1 to 0.3		

LITERATURE REVIEW

Although LF intuitively seemed to be the best measure of level of service, subsequent problems (2, 3, 4, 5, 6, 7, 8) did arise. May (3, 8) noted the absence of any rational basis for finding breakpoints in LF to define various levels of service. Furthermore, Pontier, Miller, and Kraft (4) and Reilly, Miller, and Jagannath (5) observed that the identification of loaded cycles required considerable judgment on the part of field observers.

Instead of an LF, the former authors (4) used a saturation factor, which they defined as "the number of saturated cycles divided by the total number of cycles during a specified time period." A saturated cycle is any cycle during which the number of vehicles stopped on red is greater than the number of vehicles passing through on the following green.

May and Pratt (3) and May and Gyamfi (6) used LF to correlate levels of service to average individual delay (AID). They took equal delay intervals as a possible basis for the choice of LF values to define various levels of service.

Tidwell and Humphreys (7) presented an alternative procedure that utilized a cycle failure rate to indicate level of service for pretimed signalized intersections. These authors defined a cycle failure as "any cycle during which approach arrivals exceed the capacity of departures." The cycle failure rate is predicted as a probability of arrivals exceeding departure capacity by using a cumulative Poisson distribution. The same authors investigated the feasibility of using AID as an index of level of service offered by a signalized intersection. They argued that, if speed is the criterion for uninterrupted flow conditions, a delay index can be used for intersection operation.

Sagi and Campbell (2) also observed that vehicle delay is a more satisfactory and inherently more useful criterion for assessing levels of service at signalized intersections. The recent Intersection Capacity Workshop (9) too voiced concern regarding the use of LF.

USER-RATING CONCEPT

The above review indicates that future research must

1. Establish, if possible, a rational basis for relating level of service and LF,
2. Check the validity of a hypothesis that LF is a better predictor of level of service than AID, and
3. Establish a relationship between AID and LF at a given level of service.

Our premise is that the quality of flow at any intersection should reflect the attitudes of the road users. There are different levels of satisfaction regarding intersection operation, and it was felt that the opinions of a group of road users could be used to establish a rational relationship between LF and levels of service. This would involve a compilation of all the road users' inclinations, feelings, and degrees of satisfaction about the quality of service at an intersection. We also contend that the service an intersection has been designed to provide might reflect both objective and perceived attributes or dimensions and that there exists a function by which the one can be related to the other. Thus drivers' subjective ratings of quality of flow at a signalized intersection would represent their attitutes or opinions, and LF, AID, or saturation factor would represent an objective rating.

We conducted a literature survey to determine the feasibility of using a user-response or attitude approach, and decided that, because such an approach had been successfully utilized (10, 11, 12) previously, it could provide meaningful results (13, 14).

Our research objectives were (a) to develop the necessary procedure for applying this user-rating concept, (b) to check the validity of the hypothesis that LF is a better predictor of level of service than AID, and (c) to establish a relationship between AID and LF at a given level of service for signalized intersections. These objectives are discussed in detail in the following pages.

APPLICATION OF THE CONCEPT

The steps we took in developing the concepts in this study are described in the following.

Step 1. Selection of a Typical Signalized Intersection

Because the 1965 HCM (1, pp. 111-159) deals primarily with fixed-time or pretimed signal controls, we studied 30 isolated fixed-time intersections for feasibility in the Dallas-Fort Worth area. It was disappointing, therefore, that not one of the 30 could either satisfy the criteria for a full range of load factors or offer a vantage point for an unobstructed overall view for film coverage. As an alternative, a fully actuated signalized intersection located at Lemmon and Oaklawn avenues in Dallas was selected as the best alternative.

Step 2. Conducting Field Studies

Before filming various traffic situations representing levels of service, a number of field studies were carried out during several selected hours and days on the westbound Oaklawn Avenue approach to the intersection. These field studies included:

1. Automatic traffic volume counts for a full week;
2. Manual traffic volume counts to determine directional distribution, vehicle composition, and peak-hour factor (PHF) (1);
3. Delay studies to estimate AID during selected hours [the Sagi and Campbell method (2) was employed because of its sound theoretical approach, its suitability for a fully actuated signal control, and its applicability to all levels of traffic volume, including oversaturation], and the resulting values shown in Table 1 for the selected westbound approach; and
4. LF measurements determined by the number of loaded cycles during the selected hours [a green phase was considered loaded when the following conditions (1) existed: (a) vehicles in all lanes were ready to enter when the signal turned green; and (b) vehicles in all lanes continued to be available to enter, with no long spaces between them during the entire green].

The measured LF [LF(M)] and AID values are tabulated in Table 1. The interpolated LF for the various volumes and the volume to capacity ratios (V/C) were obtained by referring to Figure 6.8 of the 1965 HCM (1, p. 154). The intersection of lines projected from the scale of the unadjusted service volume in vehicles per hour of green (VPHG) for standard or average conditions (1), and from the scale of approach width, identified the interpolated LF, from which the prevailing levels of service were specified. The observed variation between measured

and interpolated LF may have been caused by uncertainty in the identification of loaded cycles and by the insensitivity of LF to low service volumes.

Step 3. Preparation of Film for Rating Survey

For the purpose of this research, a microview was defined as a filmed scene showing a traffic situation that an individual driver seated in his automobile would experience while driving through the intersection. A macroview was defined as a filmed scene showing the overall traffic situation on the given approach of the intersection from high above.

Film scenes or segments representing various specific levels of service were contemplated, for a duration of one (or two) signal cycles. It was thus necessary to know the within-the-hour variation in LF values and queue lengths, so that the total collection of filmed scenes would include a full range of known levels of service. Therefore, LF values and maximum queue lengths (Q_{max}) (based on a 15-min time interval) were plotted. By observing Q_{max} on the approach, an LF estimate could be made simply by referring to this plot. Thus the "wait 'n watch" strategy during the hour helped us to decide when to film microviews and macroviews for the various levels of service. The films were taken with a 16-mm camera at 16 frames/s. The final film was prepared from one or two representative film segments for each level of service. The final film included both types of view, and the order of the segments in each type was determined purely on a random basis. The final film contains the segments listed in Table 2.

Table 1. Summary of results.

Time	Day	AID[a] (s)	LF(M)
8:00 to 9:00 a.m.	Sunday 12/8/74	23.39	0.000
7:00 to 8:00 a.m.	Tuesday 11/26/74	44.36	0.353
10:00 to 11:00 a.m.	Tuesday 11/26/74	35.89	0.143
10:00 to 11:00 a.m.	Tuesday 5/21/75	45.00	0.357
12:15 to 1:15 p.m.	Wednesday 11/27/74	64.73	0.885
12:00 n. to 1:00 p.m.	Wednesday 5/21/74	61.33	0.875
2:00 to 3:00 p.m.	Wednesday 11/27/74	52.68	0.536
2:00 to 3:00 p.m.	Friday 5/16/75	57.29	0.560
4:00 to 5:00 p.m.	Friday 5/16/75	62.98	0.905
4:00 to 5:00 p.m.	Friday 12/6/74	62.31	0.730
8:00 to 9:00 a.m.	Saturday 5/10/75	27.05	0.070

[a]Sagi and Campbell method (2).

Table 2. Duration of film segments.

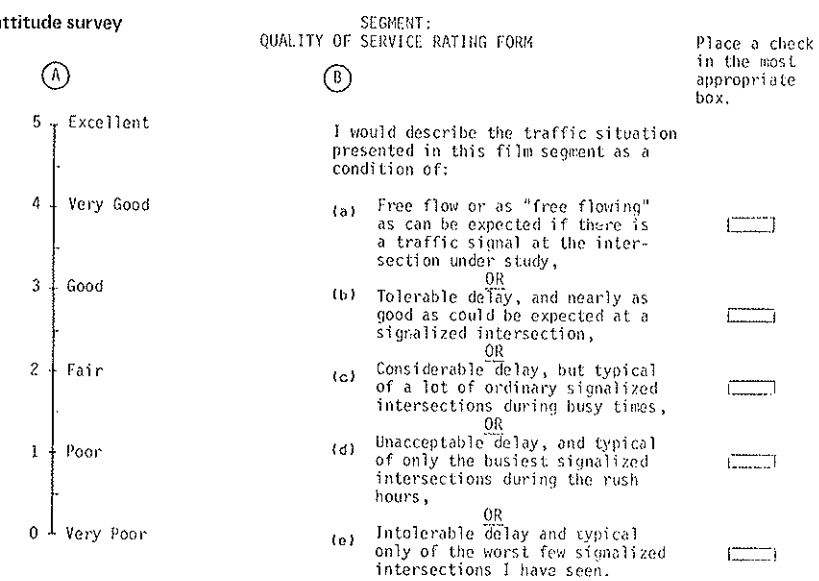
View	Segment No.	Duration of Film at 16 Frames/s (s)	Assigned LF	Level of Service
Micro	1	52	0.070	B
	2	61	0.143	C
	3	70	0.070	B
	4	42	0.000	A
	5	52	0.143	C
	6	108	0.353	D
	7	193	0.885	E
Macro	8	53	0.000	A
	9	62	0.536	D
	10	95	0.143	C
	11	121	0.905	E
	12	109	0.070	B
	13	126	0.143	C
	14	69	0.070	B

Step 4. Conducting Rating Sessions for Group Attitude Survey

A questionnaire was developed for the group attitude survey. In all, 310 respondents participated in the survey at several sessions. After they answered the first part of the questionnaire, which inquired about sex, age, and driving experience, they were requested to indicate their opinions regarding the importance, to quality of service, of five factors: delay, number of stops, traffic congestion, number of trucks and buses, and difficulty of lane changing. Then the first part of the microview film was presented to them segment by segment. Each segment consisted essentially of a driver's view of approaching, waiting, then finally passing through the intersection. After each segment the group were requested to rate traffic operations on two different opinion scales (Figure 1) with regard to level of service provided. After rating each of the seven microviews, they rated the macroviews. These macroviews presented a bird's-eye view of the approach during about one complete cycle of operation.

After the presentation of the film, they were requested to again rate the five factors regarding quality of flow at the intersection. This was done in order to

Figure 1. Scale A and scale B of the attitude survey questionnaire.



find out if the films influenced their first opinions.

Step 5. Analyzing the Data

From the field studies of the intersection approach, the four functional relationships established by using linear and curvilinear regression analysis (15, 16) are case 1, V/C ratio versus AID; case 2, AID versus LF(M); case 3, Q_{max} versus LF(M); and case 4, V/C ratio versus LF(M). The statistical analysis indicated that only case 2 was significantly curvilinear, suggesting that a second degree polynominal had a slightly better fit than a straight line (17). For the remaining cases, linear regression fit was adequate (17).

The analysis of the first part of the survey questionnaire is summarized in percentages as follows:

1. Sex: male = 72.9, female = 27.1;
2. Age group: under 25 years = 46.5, 25 to 50 years = 41.6, 51 to 65 years = 3.9, over 65 years = 8.1;
3. Driving experience: under 4 years = 35.8, 5 to 10 years = 36.5, over 10 years = 27.7;
4. Education: high school only = 33.2, some college = 52.3, college graduate = 10.3, college postgraduate = 4.2; and
5. Driving experience (the three percentages refer to little, average, and much experience respectively): downtown = 50.0, 37.4, 12.6; residential areas = 18.4,

Table 3. Summary of ratings for importance of factors to quality of flow.

	Before Rating Film Segments				After Rating Film Segments			
Factor	Mean	Standard Deviation[a]	Median	Rank	Mean	Standard Deviation[a]	Median	Rank
Delay	1.990	1.041	1.792	1	1.923	0.938	1.783	1
Number of stops	2.323	0.978	2.340	2	2.432	1.034	2.439	3
Congestion	2.426	1.106	2.332	3	2.226	0.921	2.154	2
Trucks and buses	3.568	1.220	3.524	5	3.742	1.190	3.726	5
Lane changing	2.703	1.232	2.633	4	2.887	1.090	2.910	4

[a]Very much = 1; above average = 2; average = 3; below average = 4; very little = 5; and no = 6.

Table 4. Level of service rating on continuous scale A.

View	Segment No.	Mean	Standard Deviation[a]	Median	Mode	Kurtosis	Skewness
Micro	1	3.066	0.883	3.049	3.000	0.161	-0.080
	2	2.497	0.771	2.591	3.000	-0.014	-0.178
	3	2.622	1.078	2.550	2.000	-0.483	0.021
	4	3.588	0.957	3.886	4.000	0.584	-0.576
	5	2.651	0.959	2.897	3.000	-0.119	-0.100
	6	1.937	0.977	1.971	2.000	-0.215	0.159
	7	0.893	0.841	0.946	1.000	1.013	0.937
Macro	8	3.440	0.969	3.472	3.000	-0.281	-0.445
	9	2.425	0.979	2.125	2.000	-0.069	-0.046
	10	2.299	0.854	2.125	2.000	0.106	-0.063
	11	1.259	0.849	1.020	1.000	-0.505	0.231
	12	2.989	0.898	2.999	3.000	0.145	-0.246
	13	2.936	0.947	2.979	3.000	0.416	-0.915
	14	3.405	0.867	3.396	3.000	-0.016	-0.220

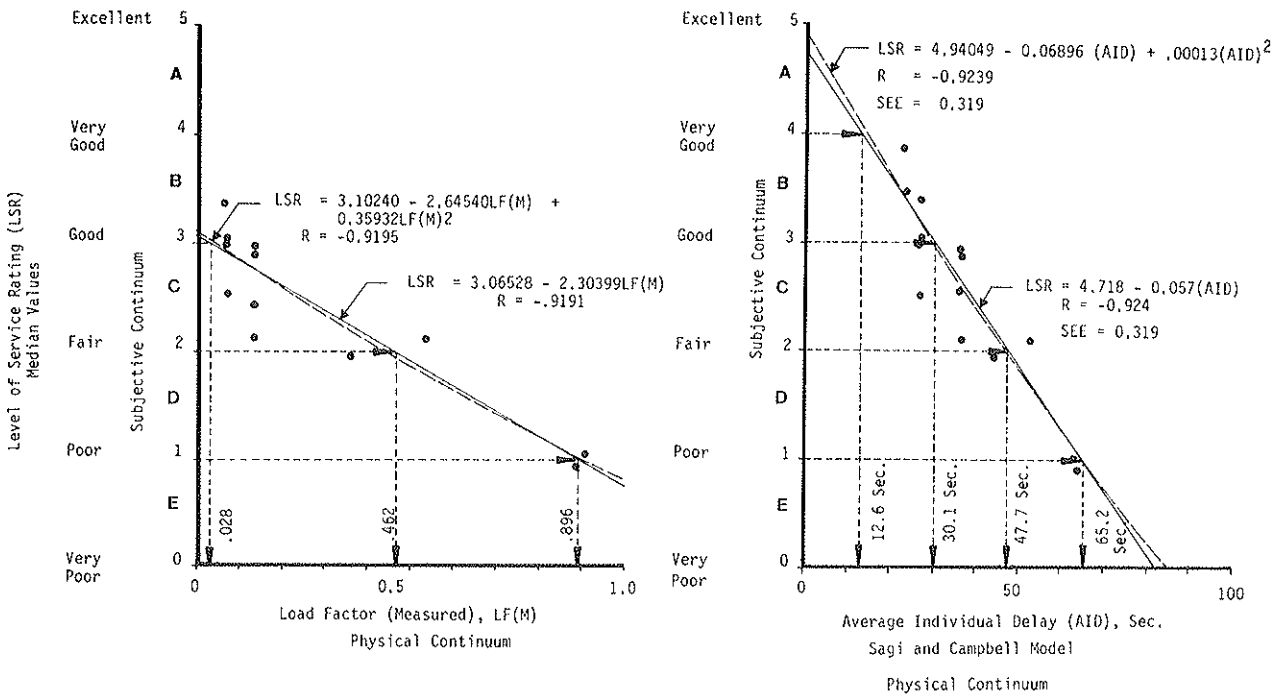
[a]Very poor = 0; poor = 1; fair = 2; good = 3; very good = 4; and excellent = 5.

Table 5. Level of service rating on point estimate scale B.

View	Segment No.	Mean	Standard Deviation	Median	Mode	Kurtosis	Skewness
Micro	1	1.981 3.774[a]	0.784	1.947	2.000	0.126	0.518
	2	2.590 3.013[a]	0.794	2.594	3.000	0.376	0.284
	3	2.539 3.076[a]	1.041	2.500	2.000	-0.487	0.284
	4	1.574 4.283[a]	0.796	0.000	1.000	2.826	1.568
	5	2.468 3.165[a]	0.919	2.403	2.000	-0.355	0.270
	6	3.229 2.214[a]	0.946	3.219	3.000	-0.251	-0.126
	7	4.174 1.033[a]	0.814	4.236	4.000	1.518	-1.050
Macro	8	1.545 4.319[a]	0.761	0.000	1.000	3.656	1.680
	9	2.606 2.993[a]	1.018	2.582	3.000	-0.323	0.291
	10	2.865 2.669[a]	0.871	2.872	3.000	-0.024	0.118
	11	3.868 1.415[a]	0.847	3.939	4.000	0.460	-0.643
	12	2.048 3.690[a]	0.904	1.975	2.000	0.626	0.749
	13	2.168 3.540[a]	0.916	2.084	2.000	0.083	0.599
	14	1.713 4.109[a]	0.758	1.650	2.000	2.417	1.200

[a]Transformed mean comparable to scale A (scale A = 6.25 to 1.25 (scale B)).

Figure 2. Two psychophysical models.



44.2, 37.4; urban freeways = 29.7, 43.9, 26.5; rural highways and freeways = 33.9, 43.2, 22.9.

The second part of the questionnaire had three subdivisions. The analysis of subdivisions 1 and 3 is presented in Table 3. Examining the mean or median ratings, we found that the delay was considered the most important factor both before and after viewing the film segments. The analysis of subdivision 2 is presented in Tables 4 and 5.

To determine the inconsistency in the interpretations of scales A and B, scale B ratings were transformed to equivalent scale A ratings as shown in the tables. The average level of service ratings of scale A were plotted against those of transformed scale B to obtain the deviation of the fitted line from a slope of 1 representing an inconsistency factor. In this particular case, the value was 0.1667.

TESTING THE HYPOTHESIS

For the purpose of testing the hypothesis that LF is a better predictor of level of service than AID, two psychophysical models, level of service rating versus LF(M) and level of service rating versus AID, were formulated as shown in Figure 2. The median values were preferred over the mean values mainly because the former are much less likely to be displaced than the latter in the case of skewed distribution. Both models were developed by a simple linear and curvilinear regression analysis, and a significance test of curvilinearity revealed that the linear regression was a better fit for both.

A hypothesis about the models fitting the data points was tested (17). It was concluded from this analysis that neither model suffered from lack of fit. (Both models fit reasonably well.) Examining the psychophysical model (a) in Figure 2, it is clear that the LF range of 0 to 1 does not encompass the full range of level of service rating from excellent to very poor. It may be that the LF could in some instances have had a negative value, which in its current definition (1) has little or no meaning. In other words, zero LF as defined in the 1965 HCM is insensitive to low service volumes. This can be explained by a plot of LF versus V/C ratio obtained from Figure 6.8 of the 1965 HCM for 6.1, 9.1, and 12.2 m (20, 30, and 40 ft) approach widths. This plot reveals that the zero LF cannot discriminate between V/C ratios below 0.68 (17).

After the above discussion of these two models, the hypothesis that LF is a better predictor of level of service than AID cannot be said to hold. This strongly supports the argument (2, 3, 6, 8) that the definition of level of service as a function of LF (1) is not adequate. These results have once again raised the same question May (8) raised: Can a load factor of less than 0.0 be obtained?

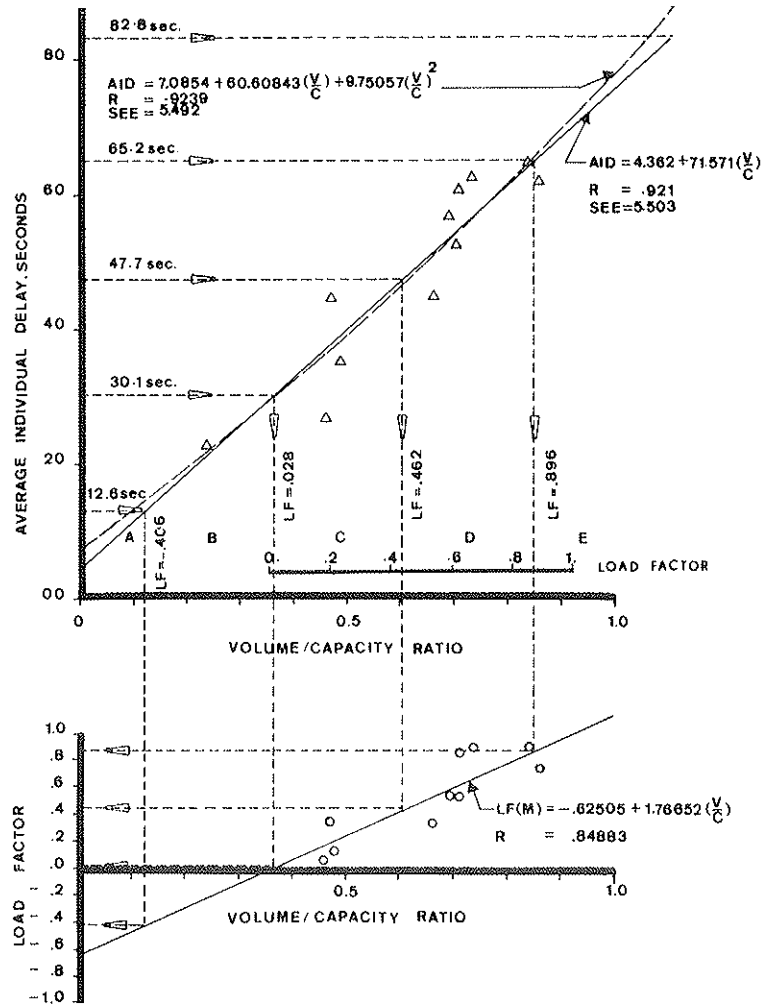
NEW RELATIONSHIPS AMONG LF, AID, V/C RATIO, AND LEVEL OF SERVICE

The two psychophysical models of Figure 2 provide a basis for establishing the breakpoints for LF and AID for defining various levels of service, based on attitudes of road users. These breakpoint values are obtained as follows (Figure 2): (a) draw horizontal lines (representing different levels of service) from the level of service rating scale to regression curve, and (b) from the point of intersections obtained in (a), project vertical lines down to LF or delay scale to obtain breakpoints. A plot (17) of the breakpoints of LF versus the breakpoints of AID would therefore depict the relationship between LF and AID at a given level of service as

$$LF(M) = -0.717\,33 + 0.024\,729\ AID \qquad (1)$$

The breakpoints as shown in Figure 3 and the previously developed functional relationships of AID versus V/C ratio and LF(M) versus V/C ratio helped in the construction of the nomograph illustrated in Figure 3. This nomograph presents the interrelationships among AID, LF, V/C ratio, and the perceived or rated level of ser-

Figure 3. New relationship among LF, AID, V/C ratio, and level of service.



vice. The LF scale of 0 to 1 superimposed on this figure is for comparison. Note that the relationship between levels of service and LF is different from that given in the 1965 HCM.

One could make practical use of these results to estimate the level of service at a signalized intersection approach by first obtaining the AID. The Sagi and Campbell method is recommended for measuring delay in the field. However, other methods such as the test-car (19), the time-lapse photography (17, 19), the Berger-Robertson (18), or the sampling (19) may be used by applying appropriate corrections for the variation between these methods and Sagi and Campbell's. The problem of wide variation in delay results has been addressed to some degree (17). AID could also be estimated by utilizing a known or anticipated V/C ratio. After obtaining AID (or V/C ratio), the nomograph can be used to determine the corresponding level of service.

It should be noted that the nomograph of Figure 3 was developed from the only study of the single, not ideal, signalized intersection. However, the methodology presented could be used to develop similar nomographs for any fixed-time signalized intersections. Applied to a sufficient number of different types of signalized intersections, it would provide a rational basis for establishing intersection level of service and would overcome the problems associated with (a) the present troublesome definition of the LF and its accompanying measurement difficulties and (b) the arbitrarily or intuitively chosen breakpoints for the various levels of service that do not now adequately encompass the full range of traffic volumes.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions resulted from this research.

1. The hypothesis that LF is a better predictor of level of service than AID was tested and was rejected.
2. The entire LF range of 0 to 1 failed to encompass all levels of service A through F (5-1) and indicated that LF values less than zero were required for ratings 5 and 4 (levels of service A and B). In other words, LF is insensitive to low service volumes.
3. AID, on the other hand, did correlate slightly better to levels of service rating than LF. It also encompassed all categories of levels of service rating. In addition, road users rated delay highest of the various parameters influencing levels of service at signalized intersections.
4. A new relationship was developed among AID, LF, V/C ratio, and level of service based on attitudes or perception. These relationships seemed to overcome the problems associated with using LF as the criterion for establishing the level of service. The resulting nomograph affords flexibility in the sense that one could predict level of service not only from LF, but also from AID and V/C ratio.

The following recommendations are made in view of the results of this study and the experience gained by it:

1. AID not LF should be used for predicting level of service, because AID provides a rational, meaningful, and inherently more useful predictor;
2. A fully actuated signalized intersection had to be used for this study, and similar studies should be carried out on a number of different kinds of signalized intersections; and
3. A simultaneous filming and field traffic studies procedure should be used because it eliminates the assignment of approximated LF values to film segments.

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Estimation of Unprotected Left-Turn Capacity at Signalized Intersections

Daniel B. Fambro, Carroll J. Messer, and Donald A. Andersen, Texas Transportation Institute, Texas A&M University

A mathematical model was developed to calculate the unprotected left-turn capacity of a pretimed signalized intersection. The capacity depends primarily on the volume of traffic opposing the left-turn movement and the percentage of the cycle available for this maneuver. Parameters were determined from field studies conducted in several Texas cities. The model was used to estimate the unprotected left-turn capacity for approaches both with and without exclusive turn lanes. Opposing volumes ranged from 200 to 1000 automobiles/h in one, two, or three lanes. Green splits from 30 to 70 percent of the cycle were analyzed. Unprotected left-turn capacities as predicted by the model and by the Highway Capacity Manual were compared. General agreement was found at a 50 percent green split; significant differences existed at other green splits.

The Highway Capacity Manual (1, pp. 139-140) states that the service volume (capacity) of an unprotected movement with a left-turn bay of adequate length is equal to the "difference between 1,200 vehicles and the total opposing traffic volume in terms of passenger cars per hour of green, but not less than two vehicles per signal cycle." If a left-turn lane is not provided, an adjustment factor based on the percentage of traffic turning left is used to determine the capacity of that approach. This adjustment varies with street width and available parking. However, as demonstrated by a study at Northwestern University (2), this factor does not reflect the effects of different levels of opposing traffic flow.

The Australian method (3, 4) of estimating capacity utilizes a left-turn equivalency factor for opposed left turners based on opposing vehicle volume. The Metropolitan Toronto Roads and Traffic Department (5) uses gap acceptance criteria to estimate the left-turn capacity of two- or three-lane streets having an exclusive turn lane without an exclusive phase for the turning move-