Prioritizing Signalized Intersection Operational Deficiencies

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A two-level screening process is described for evaluating short- to medium-term improvements for signalized intersections, and a procedure is developed for evaluating and ranking intersection operational deficiencies. A deficiency index (DI) is developed using a linear utility function. A detailed description is provided of the criteria evaluation and selection process used to screen 21 candidate criteria and to select the final formulation of the deficiency index. Also provided is a description of the analysis procedure used to determine the final weights applied to the factors in the DI operation. The use of the DI is demonstrated through the rating of operational deficiencies for all 286 signalized intersections in Tucson, Arizona. The DI is used to identify the 30 intersections most in need of operational improvements.

An essential element of transportation planning and traffic engineering is knowledge of the existing conditions of the roadway system. This knowledge supplies the basis for decisions regarding highway system improvement, improvement priorities, and the staging of improvement implementation. The knowledge of the existing capacity and level of service (LOS) of the elements of the roadway system also supplies a basis for measuring the impact of land development and community growth. The capability of an element of the roadway system (for example, an intersection or highway segment) to accommodate an increase in demand resulting from nearby land development can only be accurately assessed with a clear understanding of the current vehicle demand and roadway capacity. The proper assessment of highway improvement needs requires the knowledge of current and anticipated deficiencies. This knowledge is particularly important with respect to signalized intersections, which typically establish urban arterial system capacity and operating conditions.

Local jurisdictions typically maintain a process by which highway system improvement needs are identified, prioritized, and included in an annual capital improvement program (CIP). The impetus for this study was a concern of the city of Tucson (COT), Arizona, that its existing process for identifying, evaluating, and prioritizing arterial improvements (particularly at signalized intersections) did not provide sufficient information for rational technical decisions regarding improvement needs and priorities. This was of particular concern in light of the city's inability to fund large-scale, long-term transportation improvements because of lack of funding. Also of concern were recently adopted policies limiting roadway widening and establishing a LOS D threshold for the initiation of a planning study for urban arterials. Therefore, the city has established a position of attempting to maximize short-term congestion relief with the available funds, at the same time attempting to identify arterial corridors exceeding the LOS threshold, permitting study for long-term improvement implementation.

The primary goal of this project was to provide COT with a comprehensive information data base and evaluation procedure in order to assess the existing operating conditions of the city's signalized intersections and to evaluate existing intersection improvement needs and priorities. This study focused on individual congestion hot spots and low-cost improvement alternatives for providing short- to medium-term relief. The procedures developed and presented were not intended to replace the long-range comprehensive planning process or the implementation of long-term transportation improvements. Instead, these procedures were intended to supplement long-range planning and to provide direction in the selection of shorter-term improvements in lieu of factors that prevent the immediate implementation of a long-range system plan.

The goal was reached in part through the satisfaction of the following objectives:

1. Provide an accurate and quantified assessment of the current operating status of the city's signalized intersections.
2. Develop a rating system for prioritizing intersection improvements on the basis of criteria that reflect the existing improvement needs, and establish this rating system in a microcomputer-based software program.
3. Establish a data base management system to enable the city to maintain an up-to-date assessment of intersection improvement priorities using the developed software.
4. Develop alternative concept designs to alleviate problem conditions for the worst 30 intersections identified and prioritize these improvements based on cost-effectiveness.

A detailed description of the elements of this entire study is provided in the final report (*1*). The following discussion details the procedures developed to identify and prioritize signalized intersection operational improvement needs. This procedure was developed to establish a short list of 30 intersections most in need of operational improvements. This procedure was intended to provide a focus for the analysis of improvement alternatives at these 30 locations. The discussion of the improvement alternatives analysis and cost-effectiveness ranking of improvements is described in a companion paper by Witkowski in this Record.

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EXISTING COT PROCEDURES

A summary of the previous COT process for identifying intersection and roadway segment improvement needs is shown in Figure 1. The initial screening of signalized intersections was based on intersection accident history using intersection accident rate stratified by the functional classification of the intersecting roadways as the evaluation criterion.

Information on intersection geometric or operational conditions was not explicitly included in the previous analysis procedure. These intersection characteristics were evaluated after the intersections of concern had been identified on the basis of accident history. Therefore, intersections with operational deficiencies (i.e., long delays or poor level of service) were not identified as intersections of concern unless they had a high accident rate. Poor intersection operating conditions may not necessarily result in a high intersection accident rate, and intersection safety problems may not necessarily be alleviated through improvements in intersection operations. Therefore, the previous evaluation process failed to provide information vital to the assessment of intersection operational improvement needs.

The city's previous procedure for determining roadway segment improvement needs, including major widening, was based on a sufficiency rating analysis. This sufficiency rating is based on the physical condition of the street, considering pavement structural condition, maintenance needs, traffic congestion (present and forecast), and accident history. A point system is used to quantify each criterion, and the points are combined to provide an overall assessment of roadway condition. Sufficiency rating systems of this type have been commonly used by state and local transportation agencies for many years (*2*).

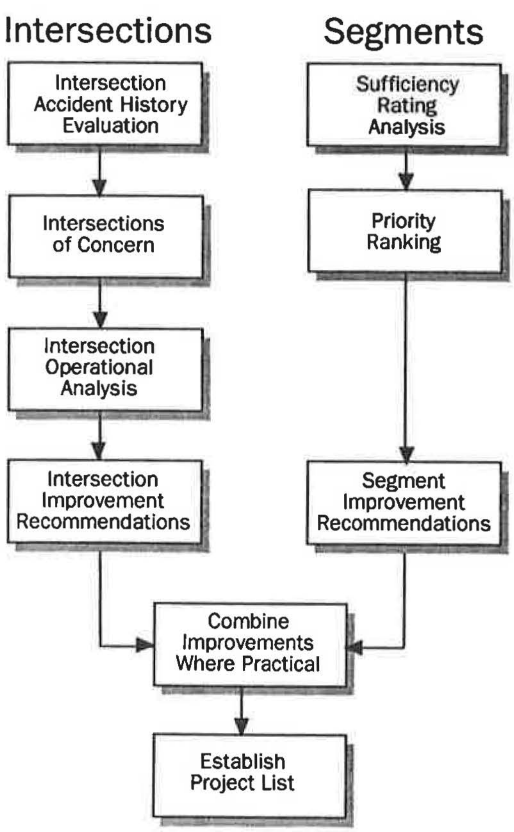

FIGURE 1 Overview of current COT intersection and roadway segment evaluation process.

OPERATIONAL VERSUS SAFETY IMPROVEMENTS

There appears to be a clear dichotomy in the evaluation of intersection improvement needs. This dichotomy arises from the need to identify both safety and operational deficiencies and the improvements that are specifically designed to address each type of problem.

The need for this dichotomy also becomes apparent with the consideration of the potential liability created by evaluating safety and operational deficiencies together and evaluating improvement needs on the basis of a combined deficiency index (DI). There is a potential for a needed safety improvement not being identified because it is somehow overshadowed by intersections with high operational deficiencies. The analysis procedure must be capable of identifying both safety and operational improvement needs separately. Therefore, a procedure was developed to identify intersection operational and safety deficiencies separately and to combine improvement recommendations when an analysis indicates that the combination is practical.

The recommended analysis procedure for establishing intersection improvement priorities is shown in Figure 2. The prioritization procedure is a two-screen process. In the first screen, all intersections under analysis are evaluated separately for both safety and operational deficiencies using selected evaluation criteria and given a separate rating for both safety and operational improvements. The deficiency rating is an indication of the overall need for improvement at each location.

After the first screen, intersections with the highest deficiency rating are selected for a more detailed assessment of problems and potential solutions. Requirements for safety and operational improvements are compared in order to determine where improvements should be combined because they address related problems. In addition, intersection safety and operational improvement needs are compared and coordinated with other system improvements. The comparison with other system improvements identifies where intersection improvements can be combined with planned major facility upgrades. This comparison also provides for an evaluation of the continuity of improvements in a systemwide context.

The second screen in the analysis procedure is an evaluation of cost-effectiveness. The cost-effectiveness analysis is used to establish the final improvement priorities for operational and safety improvements.

The cost-effectiveness evaluation of safety and operational improvements should be performed separately when the improvement requirements cannot be combined at a given location. The rationale for this is that operational improvements typically generate much higher cost-effectiveness values than safety improvements. Therefore, it would be difficult for purely

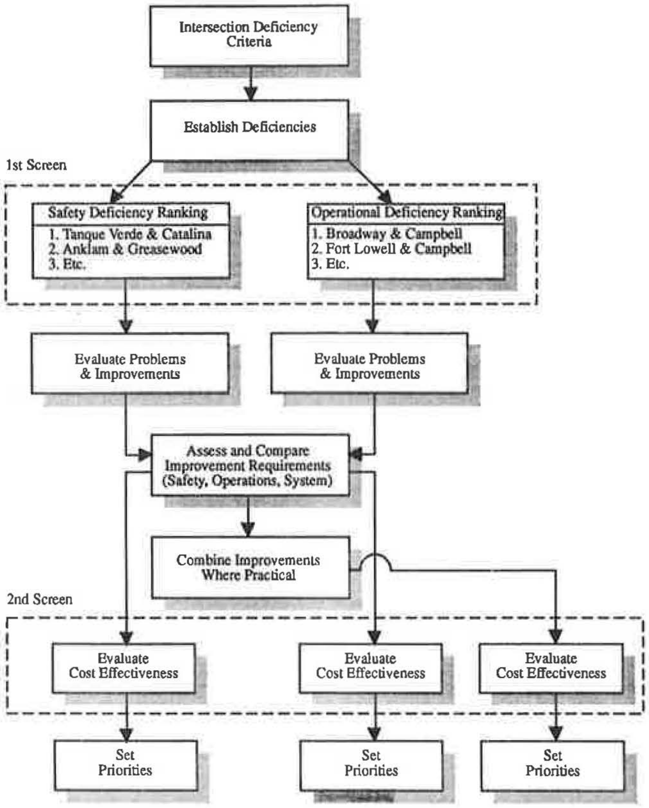

FIGURE 2 Recommended intersection analysis procedure.

safety-related improvements to compete for improvement funds. However, making no safety improvements at locations with identified problems places municipalities in a poor position relative to potential liability in accident cases that occur at these locations. Potential liability is not a parameter that has been included traditionally in the cost-effectiveness of safety improvements, but it must be considered as an important element in the justification of the dichotomy of safety and operational improvement categories.

OPERATIONAL DEFICIENCY CRITERIA

The criteria used in the analysis of operational deficiencies are of primary importance in the successful identification of improvement needs. The criteria must possess several important characteristics. For the purposes of this study, these characteristics were defined as follows:

- Technical reliability—The level of each criterion must vary with the operational condition of the intersection. The level of the criteria must be obtained with sufficient measurement-estimation accuracy to provide a useful and reliable evaluation tool.
- Importance—The criteria must convey a measure of importance in the evaluation of improvement needs. It must be related meaningfully to the operational condition of the intersection.
- Availability—The measure or estimate of each criterion should be available and updated periodically without unreasonable expense or level of effort.
- Independence—The measure of each criterion should be unique in terms of the operational condition it represents relative to the operational condition represented by other criteria. This avoids double-counting or the weighting of a particular operational condition too heavily.

The selection of evaluation criteria for operational improvements was focused on five major categories:

- Traffic volume,
- Present peak-hour traffic conditions,
- Safety,
- Air quality, and
- Transit operations.

Conformance with design standards was considered an additional category but was eliminated early in the review process. This category was eliminated because it was considered a primary factor in the evaluation of improvement alternatives for both operational and safety problems after the problem had been identified through other criteria.

Twenty-one individual evaluation criteria from these five categories were evaluated for inclusion in the procedure for establishing intersection operational deficiencies. These criteria are presented in the first column of Table 1.

Each of the criteria discussed was evaluated on the four characteristics of technical reliability, importance, availability, and independence. A subjective evaluation was performed and each criterion was rated on a scale of 1 to 5 for each of the first three characteristics. A value of 1 was considered the lowest and 5 the highest in each of the criteria categories. Criteria were only rated against other criteria in the same category. This rating is also presented in Table 1.

The independence characteristic was evaluated by noting whether a criterion was related to any of the other criteria and a notation was made as to what measure the criterion represented. This information is also presented in Table 1.

The results of the criteria assessment are presented in the last column of Table 1. The criteria screening process led to the initial indication of those criteria that would be suited for inclusion in an intersection operational deficiency rating model. This assessment also indicated criteria that might not be suited for use together in the same deficiency rating formulation.

Two sets of preliminary operational DI criteria resulted from the criteria assessment. The criteria included in each of the sets are presented in Table 2. These criteria were subjected to further, more detailed evaluation. The final recommended criteria were selected based on a numerical assessment of each criterion measure for each intersection and an analysis of the impact of each criterion on the intersection deficiency rating.

CRITERIA VALUE ESTIMATION

The criteria in Table 2 were estimated for each of the 286 signalized intersections within the jurisdiction of COT. Afternoon peak-hour turning movement counts were taken for each intersection during the peak travel months (September through April) of 1989 and 1990. Using the operational analysis procedures for signalized intersections contained in the 1985

TABLE 1 Operational Analysis Evaluation Criteria

Evaluation Criteria	Formulation	Technical Reliability	Importance	Availability	Independence	Measure of	Preliminary Criteria Set(2)
Traffic Volume							
1. Present Average Daily Traffic (PADT)	ADT Entering	5	3	4	Related to 2., 7.	Total demand	
2. Present Peak-Hour Volume (PHV)	PHV Entering	5	5	4	Related to 1., 7.	Peak-hour demand	A
3. Forecast Average Daily Traffic (FADT)	FADT Entering	3	3	3		Future total demand	
4. Forecast Peak-Hour Volume (FPHV)	FPHV Entering	3	3	3	Factor of 3.	Future peak-hour demand	
Present Peak-Hour Traffic Operations							
5. Intersection Level of Service (LOS)	Capacity Analysis	3	4	3	Function of 2.,6.,7.	Intersection operations	
6. Intersection Critical Volume to Capacity Ratio(Xc)	Capacity Analysis	4	4	3	Function of 2.	Capacity utilization	A, B
7. Intersection Stopped Delay per Vehicle (SD)	Capacity Analysis	4	4	3	Function of 6.,2.	Intersection operations	A
8. Intersection Total Stopped Delay (TSD)	7. X 2.	4	4	3	Function of 6.,2.,7.	Operations and demand	B
9. Time Duration of LOS (TLOS)	Capacity Analysis	3	4	1	Function of 1.,2.	Operations and demand	
10. Volume per Through Lane	2./Number of Lanes	3	3	4	Function of 2.	Capacity Utilization	
Safety							
11. Total Accidents (last three years (1))	Number of Accidents	5	3	4	Related to 1.	Total Accidents	
12. Accident Rate (last three years (1))	10./1.	5	5	4	Function of 11.,1.	Accidents/unit demand	A,B,S
13. Pedestrian Accidents (last three years (1))	Number of Ped Accidents	5	4	4	Related to 1.,2.	Pedestrian safety	S
14. Bicycle Accidents (last three years (1))	Number of Bk Accidents	5	4	4	Related to 1.,2.	Bicycle safety	S
15. Accident Severity	Severity Index	4	2	4		Seriousness of Accidents	S
Air Quality							
16. Pollution Added	Grams per min. X (8.)	3	5	3	Function of 8.	Total pollution added	
17. Peak-Hour Stopped Delay per Vehicle (SD)	(7.)	4	2	3	Same as 7.	Pollution added/vehicle	
18. Peak-Hour Total Stopped Delay (TSD)	(8.)	4	5	4	Same as 8.	Total pollution added	A
Transit Operations							
19. Peak-Hour Stopped Delay per Transit Vehicle(SD)	Same as (7.)	4	3	3	Same as 7.	Transit delay per vehicle	
20. Peak-Hour Total Transit Delay (TTSD)	(7.) X # of Transit Vehicles	4	4	3	Function of 7.	Total transit vehicle delay	
21. Peak-Hour Total Transit Person Delay (TTPSD)	(20.)X Transit Load Factor	4	5	3	Function of 7.	Total transit pass. delay	A,B

1. Three years of accident data should be used to establish the accident rate unless a major intersection reconstruction has occurred during that period. Under that condition, the accident history since the reconstruction should be used, and noted as a period of less than three years.
2. A = Set A B = Set B. S = Suitable for safety deficiency index.

TABLE 2 Preliminary Operational Deficiency Rating Criteria

Evaluation Criteria Category	Set A Criteria	Set B Criteria
Traffic Volume	Present Peak-Hour Volume	
Present Traffic Operations	Critical Volume to Capacity Ratio Average Stopped Delay per Vehicle	Critical Volume to Capacity Ratio Peak-Hour Total Stopped Delay
Safety	Accident Rate	Accident Rate
Air Quality	Peak-Hour Total Stopped Delay	
Transit Operations	Peak-Hour Total Transit Person Delay	Peak-Hour Total Transit Person Delay

Highway Capacity Manual (HCM) (*3*) additional data were collected to provide the information necessary to assess the existing level of service for each intersection. The intersection stopped-delay estimates and critical volume-to-capacity ratios calculated from the HCM procedure were used as the measures of these criteria. Peak-hour total stopped delay was estimated in vehicle-hours from the average stopped delay per vehicle and the total peak-hour volume entering such intersection. Peak-hour total transit person delay was estimated in person-hours from data representing the average number of transit passengers entering each intersection during the peak-hour (provided from COT transit system records) and average stopped delay per vehicle (estimated from the HCM analysis). The constant value of 1.3 to convert stopped-delay estimates to total-delay estimates was not applied in this analysis because, as a constant multiplier, it would have no effect on the relative values of the delay estimates between intersections.

The most current 3 years of complete accident data (1986 through 1988) along with estimates of the average daily traffic entering each intersection were provided by the city. These data were used to calculate the accident rate for each intersection in accidents per million vehicles entering the intersection.

DEFICIENCY INDEX FORMULATION

A key element in the development of a prioritization process is the methodology used to combine the various criteria into a single index of operational deficiency. The purpose of the index is to identify locations that are most in need of operational improvements. The index must be technically sound, easily understood, and easily implemented, and it must generate results that can be logically supported.

The method selected for development of operational and safety deficiency indexes was a linear utility function. Linear utility functions combine weighted measures of the evaluation criteria into a single index, which is the basis for identifying improvement needs. This is the same type of procedure that is used in sufficiency rating schemes. The DI is described in Equation 1.

$$DI = W_1X_1 + W_2X_2 + \ldots + W_nX_n \qquad (1)$$

where X_i is the normalized value of criterion i and W_i is the weight applied to criterion i.

Criteria normalization precludes any single criterion from dominating the DI because of its sheer magnitude relative to the other criteria values. It also allows the criteria weights to be truer reflections of the overall importance of each criterion in determining intersection deficiencies.

There are two basic ways in which normalization can occur. The first is to normalize the value of each criterion based on its largest value for a given set of intersections. With this scheme the criteria in the DI formulation would be expressed on a zero-to-one scale, and the criteria weights would be an expression of the relative importance of each criterion in the ranking formula. The disadvantage of this procedure is that, because of possible future changes in the base for normalization, there is no way of tracking the change in intersection deficiency over time. Also, there is no way of using the DI to determine whether or not an intersection exceeds some threshold condition requiring improvement.

The second means of normalizing the criteria is to use a preselected threshold value as the base for normalization. The threshold value would be used year after year and would allow changes in intersection deficiency to be traced over time on the basis of the DI. This would also supply a basis for assessing the impact of improvements using the DI as a measure of effectiveness. The disadvantage of this procedure is that the range of normalized criteria values is not controlled as well as the previous procedure. The zero-to-one range for the criteria values cannot be maintained unless the threshold value is selected so that it cannot be exceeded. Threshold values must be set so that the integrity of the relative magnitude of the normalized criteria is maintained. The zero-to-one range for the normalized values of the criteria is not necessary as long as the relative magnitude of each criterion is maintained at a reasonable level in comparison to the weights used to value each criterion in the DI.

The threshold values for normalizing the criteria can be established in at least two ways. One possibility would be to determine the desirable maximum level, or standard, for each of the criteria keeping in mind that the range of values for the normalized values for each criterion should be approximately the same. In this way, normalized criteria values that exceed a value of one would be indicative of a condition that exceeds the desirable maximum.

Another method of establishing the threshold values would be to use the maximum values from the present condition as the threshold. This would provide a direct comparison of each succeeding year to the worst conditions that presently exist. The normalization of criteria for this study was based on the maximum value of each criterion for the existing condition.

CRITERIA ANALYSIS

The evaluation of the criteria and the selection of the final parameters to be included in the DI equations were based on an assessment of the relative interdependence of the criteria and the sensitivity of the ranking of the intersections to the criteria. The interdependence of the criteria was judged using linear regression analysis techniques. The impact of the criteria on the ranking of the intersections was based on a sensitivity analysis.

Regression Analysis

A matrix of the simple linear coefficients of determination values (r^2) was developed using linear regression analysis procedures applied to both the actual and normalized criteria values. There was virtually no difference between the coefficients generated using the actual and normalized values. For brevity only the results using the normalized values are presented here.

The linear regression analysis results are presented in Table 3. The mean and standard deviation of each of the variables are presented along with the r^2 values.

In general, variables that are highly correlated should not be used together in the relationship for the DI because they represent a redundant explanatory power and would double count for the same effects. Therefore, stopped delay per vehicle and total stopped delay were judged to be too highly correlated to appear in the same DI formulation, as were total stopped delay and peak-hour volume. Further refinement of the DI criteria was based on a sensitivity analysis.

Sensitivity Analysis

A sensitivity analysis was performed to determine the sensitivity of the deficiency rating of the intersections to the operations criteria. The base-case rating that included each of the criteria with an equal weight in determining the DI was established. Systematically, one variable at a time was removed from the DI equation, and the intersections were rated with the remaining variables having equal weight. The ratings with the deleted variable were compared to the base case, and the changes in rank of the 30 highest-rated intersections in the base condition were determined. An overall sensitivity index was calculated as the sum of the absolute value of the change in rank for the 30 intersections rated highest in the base condition. The results of the sensitivity analysis are presented in Table 4.

The rating of intersections showed very little sensitivity to accident rate and the critical volume to capacity (v/c) ratio. These variables added little explanatory power to the analysis. In order for accident rate and the critical v/c ratio to affect the results of the DI rating to any significant degree, the weights applied to these parameters in the DI equation would have to far exceed their relative importance as operations analysis parameters. Therefore, these variables were excluded from the DI.

TABLE 4 Operational Criteria Sensitivity Analysis

		Variable Deleted						Variable Deleted					
Int #	Base	PV	Acc Rate	V/C	Ave Delay	Total Delay	Trans Delay	PV	Acc Rate	V/C	Ave Delay	Total Delay	Trans Delay
		Rank						Change in Ranking					
123	1	1	1	1	1	1	1	0	0	0	0	0	0
234	2	3	2	2	3	4	3	-1	0	0	-1	-2	-1
584	3	5	3	3	2	3	5	-2	0	0	1	0	-2
575	4	2	9	4	5	2	16	2	-5	0	-1	2	-12
596	5	9	5	7	4	10	2	-4	0	-2	1	-5	3
343	6	8	4	6	6	6	8	-2	2	0	0	0	-2
348	7	10	6	8	7	11	7	-3	1	-1	0	-4	0
488	8	4	7	5	15	5	18	4	1	3	-7	3	-10
346	9	11	8	10	11	12	9	-2	1	-1	-2	-3	0
492	10	14	11	11	10	9	12	-4	-1	-1	0	1	-2
489	11	12	10	9	8	7	17	-1	1	2	3	4	-6
101	12	7	13	12	18	15	6	5	-1	0	-6	-3	6
681	13	15	12	13	14	19	4	-2	1	0	-1	-6	9
230	14	13	14	15	13	14	11	1	0	-1	1	0	3
483	15	19	18	16	9	8	20	-4	-3	-1	6	7	-5
582	16	16	15	17	20	18	19	0	1	-1	-4	-2	-3
401	17	18	16	19	16	17	23	-1	1	-2	1	0	-6
262	18	26	17	20	17	21	10	-8	1	-2	1	-3	8
341	19	21	20	18	12	16	22	-2	-1	1	7	3	-3
709	20	6	19	14	31	13	34	14	1	6	-11	7	-14
219	21	20	21	21	22	20	13	1	0	0	-1	1	8
47	22	17	22	22	32	24	21	5	0	0	-10	-2	1
600	23	31	23	23	19	23	15	-8	0	0	4	0	8
603	24	22	28	24	36	31	14	2	-4	0	-12	-7	10
504	25	32	24	25	24	26	25	-7	1	0	1	-1	0
416	26	24	25	26	28	27	26	2	1	0	-2	-1	0
223	27	28	27	29	21	22	33	-1	0	-2	6	5	-6
496	28	35	29	28	23	25	30	-7	-1	0	5	3	-2
263	29	25	26	27	38	34	24	4	3	2	-9	-5	5
408	30	27	30	30	30	29	36	3	0	0	0	1	-6
							Total Absolute Change	102	32	28	104	81	141

The most significant variables in the DI were peak-hour volume, average stopped delay, total stopped delay, and transit person delay. Because of the high correlation between total delay, average delay, and the peak-hour volume, it was recommended that all three of these variables not be contained in the same DI relationship. Two relationships were subject to further testing in order to determine the criteria weights for the DI. These relationships were (a) an equation containing total delay and transit person delay and (b) an equation containing peak-hour volume, average delay, and transit person delay. A summary of the recommendations for the criteria to be used in the DI is provided in Table 5.

Weight Analysis

The analysis of the weights to be used in the DI equation proceeded in a manner similar to that employed for the sen-

TABLE 3 Normalized Operations Data Statistics

	Coefficient of Determination (r^2)				
Variable	Average Delay per Vehicle	Peak Volume	Accident Rate	Critical v/c	Total Delay
Peak Volume	.350				
Accident Rate	.008	.005			
Critical v/c	.210	.400	.004		
Total Stopped Delay	.852	.600	.005	.279	
Transit Person Delay	.482	.257	.002	.093	.474

Variable	Mean	Standard Deviation
Average Delay per Vehicle	0.2502	0.2029
Peak Volume	0.4649	0.2047
Accident Rate	0.1555	0.0975
Critical v/c	0.2390	0.1016
Total Stopped Delay	0.1790	0.2053
Transit Person Delay	0.1357	0.1764

TABLE 5 Operational Criteria Recommendations

Included Criteria

- Total Stopped Delay and Transit Person Stopped Delay

  or
- Peak-Hour Volume, Average Stopped Delay, and Transit Person Stopped Delay

Rationale

- Rating is sensitive to these parameters
- Average delay and peak volume are logical operations measures
- For intersections with same average delay, higher volume should be ranked higher
- For intersections with same volume, higher delay should be rated higher
- Total delay combines peak volume and average delay in appropriate manner
- Average delay and total delay are highly correlated
- Transit delay adds a significant rating parameter

Excluded Criteria

- Accident Rate
- Critical v/c

Rationale

- Accident rate adds no explanatory power to operations analysis -- not correlated to operations parameters
- Accident rate included in separate safety analysis
- Rating is insensitive to accident rate
- Rating is insensitive to critical v/c

sitivity analysis. The change in intersection rankings as observed in relation to a base condition for various weights applied to the criteria in the equation. The sensitivity of the rankings to the change in the criteria was used to focus the recommendations for the final criteria.

The evaluation of the operations criteria required three separate analyses. Analysis A evaluated the criteria weight for an index comprised of total delay and transit person delay using ratings based solely on total delay as the base condition. Analysis A indicated that the intersection rankings had a low sensitivity to the inclusion of transit person delay in the relationship with a weight of 10 percent or less. These results are presented in Table 6. The rankings were moderately sensitive to transit person delay with a weight of 20 percent and exhibited a high level of sensitivity to transit person delay with a weight of 30 percent. An additional test was performed using a 15 percent weight on transit person delay and resulted in a moderate level of sensitivity in the rankings that was less than that using the 20 percent weight.

Analysis B compared the rankings using peak-hour volume and average delay as the criteria in the index with a base condition using only total delay recall. The total delay is the product of peak-hour volume and average delay. Therefore, the equation with only total delay contains both the peak-hour volume and average delay in a different form. The purpose of this analysis was to evaluate which equation provided a better overall index to be used in the ranking process. The results using various weighting schemes for peak-hour volume and average delay are presented in Table 7.

The results of Analysis B indicated that using peak-hour volume and average delay, each at a 50 percent weight, produced results very similar to those generated using only total delay in the equation. The ranking of the first 13 intersections remained unchanged, with only minor changes for the remaining intersections. Deviations from the 50 percent weights used for peak-hour volume and average delay resulted in increased change in the rankings compared to the base condition. There was no clear rationale for weighting the peak-

TABLE 6 Operational Criteria Weight Analysis A

	Test						Test				
Intersection	1A	2A	3A	4A	5A	6A	2A	3A	4A	5A	6A
		Rank					Change In Rank				
123	1	1	1	1	1	1	0	0	0	0	0
234	2	2	2	2	2	2	0	0	0	0	0
596	3	3	3	4	7	3	0	0	-1	-4	0
584	4	4	4	3	3	4	0	0	1	1	0
348	5	5	5	6	6	5	0	0	-1	-1	0
681	6	7	7	9	12	9	-1	-1	-3	-6	-3
343	7	6	6	5	5	6	1	1	2	2	1
346	8	8	8	8	8	7	0	0	0	0	1
101	9	9	10	10	13	10	0	-1	-1	-4	-1
262	10	11	12	15	18	14	-1	-2	-5	-8	-4
488	11	10	9	7	4	8	1	2	4	7	3
492	12	12	11	12	11	11	0	1	0	1	1
230	13	13	14	14	14	13	0	-1	-1	-1	0
603	14	16	17	20	25	18	-2	-3	-6	-11	-4
219	15	15	15	17	19	17	0	0	-2	-4	-2
489	16	14	13	11	10	12	2	3	5	6	4
263	17	18	19	21	23	21	-1	-2	-4	-6	-4
582	18	17	16	16	15	16	1	2	2	3	2
47	19	19	21	19	21	20	0	-2	0	-2	-1
600	20	22	22	26	27	24	-2	-2	-6	-7	-4
401	21	21	20	18	16	19	0	1	3	5	2
210	22	24	26	28	33	28	-2	-4	-6	-11	-6
416	23	23	23	24	24	23	0	0	-1	-1	0
575	24	20	18	13	9	15	4	6	11	15	9
504	25	26	25	27	26	25	-1	0	-2	-1	0
341	26	25	24	22	20	22	1	2	4	6	4
350	27	27	29	30	35	29	0	-2	-3	-8	-2
99	28	29	31	34	36	32	-1	-3	-6	-8	-4
579	29	30	30	33	34	31	-1	-1	-4	-5	-2
483	30	28	27	25	22	27	2	3	5	8	3
Total Absolute Change							24	45	89	142	67

Weight Factors Used:
Test:
1A --> Total Delay = 1.000
2A --> Total Delay = 0.950, Trans. Person Delay = 0.050
3A --> Total Delay = 0.900, Trans. Person Delay = 0.100
4A --> Total Delay = 0.800, Trans. Person Delay = 0.200
5A --> Total Delay = 0.700, Trans. Person Delay = 0.300
6A --> Total Delay = 0.850, Trans. Person Delay = 0.150

TABLE 7 Operational Criteria Weight Analysis B

	Test							Test				
Intersection	1B	2B	3B	4B	5B	6B	7B	2B	3B	4B	5B	6B
		Rank						Change In Rank				
123	1	1	1	2	3	1	1	0	0	-1	-2	0
234	2	2	2	1	2	2	2	0	0	1	0	0
596	3	3	3	3	1	3	3	0	0	0	2	0
584	4	4	4	4	4	4	4	0	0	0	0	0
348	5	5	5	5	5	5	5	0	0	0	0	0
681	6	6	6	6	8	6	6	0	0	0	-2	0
343	7	7	7	7	7	7	7	0	0	0	0	0
346	8	8	8	9	9	8	9	0	0	-1	-1	-1
101	9	9	10	10	12	10	8	0	-1	-1	-3	1
262	10	10	9	8	6	9	11	0	1	2	4	-1
488	11	11	12	13	15	11	10	0	-1	-2	-4	1
492	12	12	11	11	11	12	12	0	1	1	1	0
230	13	13	15	15	14	14	13	0	-2	-2	-1	0
603	14	16	17	17	21	17	14	-2	-3	-3	-7	0
219	15	17	16	16	17	16	16	-2	-1	-1	-2	-1
489	16	15	14	14	13	15	15	1	2	2	3	1
263	17	18	19	19	26	19	19	-1	-2	-2	-9	-2
582	18	19	20	20	25	20	20	-1	-2	-2	-7	-2
47	19	20	21	26	27	21	18	-1	-2	-7	-8	1
600	20	14	13	12	10	13	17	6	7	8	10	3
401	21	22	22	21	22	22	25	-1	-1	0	-1	-4
210	22	23	28	28	31	24	21	-1	-6	-6	-9	1
416	23	28	30	29	28	29	26	-5	-7	-6	-5	-3
575	24	24	29	30	34	27	23	0	-5	-6	-10	1
504	25	21	18	18	16	18	24	4	7	7	9	1
341	26	26	24	24	23	23	27	0	2	2	3	-1
350	27	30	27	27	24	26	29	-3	0	0	3	-2
99	28	33	34	35	35	33	34	-5	-6	-7	-7	-6
579	29	32	33	32	32	32	33	-3	-4	-3	-3	-4
483	30	29	25	23	18	25	30	1	5	7	12	0

Weight Factors Used:
Test:
1B --> Total Delay = 1.000
2B --> Peak Vol. = 0.500, Ave. Delay = 0.500
3B --> Peak Vol. = 0.530, Ave. Delay = 0.470
4B --> Peak Vol. = 0.550, Ave. Delay = 0.450
5B --> Peak Vol. = 0.600, Ave. Delay = 0.400
6B --> Peak Vol. = 0.470, Ave. Delay = 0.530

hour volume or the average delay more or less than the other. Therefore, there appears to be no advantage to using peak-hour volume and average delay over an equation containing only total delay. Total stopped delay also provides the advantage that it can be used as a surrogate for, or directly in computations of, vehicle emission levels. It also provides a good effectiveness measure for use in the economic analysis of improvement alternatives.

Analysis C evaluated the inclusion of transit person delay in the equation with peak-hour volume and average delay. The equation with peak-hour volume and average delay weighted equally at 50 percent was used as the base condition. The results are presented in Table 8. The results indicate that the rankings are considerably more sensitive to the inclusion of transit person delay in this relationship than in the relationship with total delay. In each case where total volume and average delay were weighted equally, the inclusion of transit person delay had a much greater impact on the rankings at a given weight than it did in the relationship with total delay at the same weight (Analysis A). Because of the large shifts in the rankings when transit person delay was included in the equation, Analysis C rankings were considered overly sensitive to transit delay.

TABLE 8 Operational Criteria Weight Analysis C

Intersection	Test (Rank) 1C	2C	3C	4C	5C	6C	7C	8C	Test (Change In Rank) 2C	3C	4C	5C	6C	7C	8C
123	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
234	2	2	2	2	3	2	2	2	0	0	0	-1	0	0	0
596	3	7	7	7	6	7	3	4	-4	-4	-4	-3	-4	0	-1
584	4	3	3	3	2	3	4	3	1	1	1	2	1	0	1
348	5	6	6	6	5	6	5	5	-1	-1	-1	0	-1	0	0
681	6	14	13	12	14	12	8	9	-8	-7	-6	-8	-6	-2	-3
343	7	5	5	4	4	5	6	6	2	2	3	3	2	1	1
346	8	8	8	8	8	8	7	8	0	0	0	0	0	1	0
101	9	13	14	16	20	14	10	10	-4	-5	-7	-11	-5	-1	-1
262	10	17	15	13	12	15	11	13	-7	-5	-3	-2	-5	-1	-3
488	11	4	4	5	7	4	9	7	7	7	6	4	7	2	4
492	12	11	11	11	10	11	12	12	1	1	1	2	1	0	0
230	13	15	16	17	16	16	14	15	-2	-3	-4	-3	-3	-1	-2
600	14	23	21	21	18	22	15	18	-9	-7	-7	-4	-8	-1	-4
489	15	10	9	9	9	9	13	11	5	6	6	6	6	2	4
603	16	27	29	29	31	29	17	21	-11	-13	-13	-15	-13	-1	-5
219	17	21	22	22	24	21	16	19	-4	-5	-5	-7	-4	1	-2
263	18	26	27	27	29	26	22	26	-8	-9	-9	-11	-8	-4	-8
582	19	16	18	19	19	17	18	17	3	1	0	0	2	1	2
47	20	22	24	25	26	23	20	22	-2	-4	-5	-6	-3	0	-2
504	21	24	23	23	23	24	24	25	-3	-2	-2	-2	-3	-3	-4
401	22	18	19	18	15	18	23	20	4	3	4	7	4	-1	2
210	23	34	36	38	41	36	27	29	-11	-13	-15	-18	-13	-4	-6
575	24	9	10	10	11	10	19	14	15	14	14	13	14	5	10
709	25	12	12	14	21	13	21	16	13	13	11	4	12	4	9
341	26	20	20	20	17	20	25	24	6	6	6	9	6	1	2
335	27	38	38	36	34	40	31	32	-11	-11	-9	-7	-13	-4	-5
416	28	29	28	28	28	28	28	28	-1	0	0	0	0	0	0
483	29	19	17	15	13	19	26	23	10	12	14	16	10	3	6
350	30	31	30	30	27	30	30	30	-1	0	0	3	0	0	0
Total Absolute Change									154	155	156	167	154	44	87

Weight Factors Used:
Test:
1C --> Peak Vol. = 0.500, Ave. Delay = 0.500
2C --> Peak Vol. = 0.400, Ave. Delay = 0.400, Trans. Person Delay = 0.200
3C --> Peak Vol. = 0.424, Ave. Delay = 0.376, Trans. Person Delay = 0.200
4C --> Peak Vol. = 0.440, Ave. Delay = 0.360, Trans. Person Delay = 0.200
5C --> Peak Vol. = 0.480, Ave. Delay = 0.320, Trans. Person Delay = 0.200
6C --> Peak Vol. = 0.400, Ave. Delay = 0.360, Trans. Person Delay = 0.200
Total Delay = 0.040
7C --> Peak Vol. = 0.475, Ave. Delay = 0.475, Trans. Person Delay = 0.050
8C --> Peak Vol. = 0.450, Ave. Delay = 0.450, Trans. Person Delay = 0.100

The recommended relationship for use in the rating of intersections based on operations parameters was to use total delay in combination with transit person delay. The evaluation of the assignment of weights to total delay and transit delay suggested that the use of a weight of 10 percent or less for transit person delay provided rankings that were basically insensitive to the inclusion of transit delay. A 30 percent weight on transit person delay affected the ranking results more than was deemed appropriate. The 15 and 20 percent weights on transit delay provided reasonable impacts on the ranking of the intersections. After review by city staff, the 15 percent weight for transit delay was selected in combination with an 85 percent weight on total delay. The results of the operational DI analysis are presented in Table 9 for those 30 intersections considered most operationally deficient. Note that these results differ slightly from the results generated during the evaluation of the criteria and weighting factors as a result of the final review and update of the data used in the analysis.

RESULTS AND CONCLUSIONS

The procedures developed throughout this study provide a useful element in a comprehensive congestion-management program. The identification of existing intersection operational deficiencies is a key element in establishing an effective program to reduce urban congestion, improve automobile and transit travel time, reduce vehicle emissions, and improve air quality. These procedures are intended to supplement the long-range regional transportation planning process and to provide assistance in the selection of short- to medium-term congestion relief measures by identifying those signalized intersections most in need of operational improvements. This will allow local transportation agencies to focus their manpower and financial resources on problems that will benefit the most from improvement.

It should be emphasized that the identification of hazardous intersections is an important element in the overall assessment of improvement needs. The safety analysis should be conducted separately to ensure that intersections of safety concern are properly identified and not overshadowed by the operational deficiencies. This is particularly important because the intersection accident rate was shown to be unrelated to the estimated congestion levels. Therefore, it cannot be assumed that identifying operational deficiencies will concurrently identify safety deficiencies.

The analysis procedures used to screen the criteria for inclusion in the DI provided for the rational selection of the final criteria used in the index formulation. The analysis procedures used to evaluate the weighting factors applied to each criterion provided a logical quantitative assessment.

The application of the 1985 HCM procedures for the analysis of signalized intersections was extremely valuable in the assessment of the existing operating conditions of the COT arterial system. This analysis provided the basis for the establishment of the DI and the development of the city's CIP. Future applications of the deficiency analysis will require that the capacity analysis be updated on a periodic basis with a reasonable level of effort. This can be accomplished by monitoring traffic growth trends and establishing a program to update turning movement counts as dictated by traffic growth.

TABLE 9 Thirty Intersections with the Highest Operational DI

ID #	East/West Street	North/South Street	DI	Peak Vol. (Veh/Hr)	Ave. Delay (Sec/Veh)	Total Delay (Veh-Hrs)	Transit Person Delay (Person-Hrs)
483	BROADWAY BLV	CAMPBELL AV	0.947	6228	75.4	130.442	8.755
123	FORT LOWELL RD	CAMPBELL AV	0.929	5680	88.1	139.002	4.625
234	GRANT RD	CRAYCROFT RD	0.893	6415	77.5	138.101	2.799
596	22ND ST	WILMOT RD	0.802	7224	63.8	128.025	1.134
584	22ND ST	ALVERNON WY	0.759	7167	57.2	113.876	3.654
348	SPEEDWAY BLV	WILMOT RD	0.740	6729	60.9	113.832	2.538
343	SPEEDWAY BLV	SWAN RD	0.729	6354	62.0	109.430	3.479
681	GOLF LINKS RD	CRAYCROFT RD	0.696	6052	66.6	111.962	0.703
346	SPEEDWAY BLV	CRAYCROFT RD	0.692	6408	58.7	104.486	3.065
223	GRANT RD	CAMPBELL RD	0.609	5705	53.5	84.783	5.261
262	TANQUE VERDE RD	GRANT RD	0.594	7227	47.2	94.754	0.839
219	GRANT RD	01ST AV	0.547	5456	56.3	85.326	1.486
575	22ND ST	06TH AV	0.534	3736	68.3	70.880	5.862
412	05TH ST	SWAN RD	0.513	4607	60.8	77.807	2.145
401	06TH ST	CAMPBELL AV	0.504	5603	46.9	72.995	3.400
600	22ND ST	KOLB RD	0.473	7165	37.4	74.436	1.018
416	05TH ST	CRAYCROFT RD	0.468	4627	55.5	71.333	1.865
341	SPEEDWAY BLV	ALVERNON WY	0.466	5888	41.0	67.058	3.291
335	SPEEDWAY BLV	CAMPBELL AV	0.463	6440	33.5	59.928	5.658
504	BROADWAY BLV	KOLB RD	0.447	6520	37.7	68.279	1.738
350	SPEEDWAY BLV	KOLB RD	0.405	6080	37.2	62.827	1.209
579	22ND ST	KINO PKWY	0.395	5242	41.1	60.283	1.507
582	22ND ST	COUNTRY CLUB RD	0.394	4713	44.2	57.865	2.357
99	PRINCE RD	ORACLE RD	0.391	5033	43.1	60.256	1.341
408	05TH ST	ALVERNON WY	0.385	4549	44.1	55.725	2.573
496	BROADWAY BLV	CRAYCROFT RD	0.380	6600	30.3	55.550	2.348
489	BROADWAY BLV	ALVERNON WY	0.345	6172	28.8	49.376	2.504
747	AJO WY	PARK AV	0.344	3928	49.0	53.464	0.994
587	22ND ST	SWAN RD	0.331	5904	31.6	51.824	0.790
338	SPEEDWAY BLV	COUNTRY CLUB RD	0.324	5259	30.0	43.825	3.258

Weight Factors Used:
Total Delay: 0.850 Trans. Person Delay: 0.150

The basic data base for the update of the capacity analysis was developed through the initial effort to establish the existing operating conditions. Traffic volume, intersection geometry, and traffic signal parameters must be updated periodically to facilitate future application of the developed procedures.

In situations where the duration of peak-period congestion varies between intersections, it is advisable to include a factor in the deficiency ranking that accounts for this phenomenon. A measure of the time duration of the estimated congestion levels could be used to factor the delay values used in the DI calculation.

In addition to the evaluation procedures described, a comprehensive data base management procedure was developed for COT to store information and to provide statistical analysis for both operational and safety improvement evaluation. This data base management procedure computes the operational DI and several safety-related indexes and provides numerous data-reporting and summarizing utilities. Such a data base management procedure is a key element application of these procedures as well as an application for updating the analysis in the development of future CIPs.

The procedure presented was intended to supplement long-range improvement implementation through the provision of direction for implementation of short-term improvements. An additional element that was not included in the analysis but that could prove important is the systemwide implications of improvements on the basis of the deficiencies identified. Similar procedures could be used to evaluate and rank corridors needing improvement. Also, consideration could be given to the addition of a factor in the DI to reflect a measure of systemwide importance.

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REFERENCES

1. JHK & Associates. *Tucson Transportation System Planning Study—Final Report.* Transportation Planning Division, City of Tucson, Arizona, April 1991.
2. J. M. Witkowski. Methods Used To Evaluate Highway Improvements. *Journal of Transportation Engineering*, ASCE, Volume 109, No. 6, Nov. 1983.
3. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington D.C., 1985.

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