Design Consideration for LRT in Existing Medians: Developing Warrants for Priority Treatments

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This paper examines current light rail transit planning and design criteria for at-grade crossings and suggests that an alternative criterion be used to determine if priority treatment is justified for LRT at such crossings. Current practice is assumed to be represented by the recently completed UMTA-funded research into light rail surface operations, which suggests that the appropriate evaluation criterion is the impact of light rail on the estimated level of service of the intersection of the arterial carrying light rail and the cross street. This paper, however, argues that the use of the level of service criterion significantly favors the automobile mode over the LRT mode for a wide range of automobile volumes and LRT passenger volumes because it does not consider the volume of people carried by transit. The criterion used to make this determination is the total estimated person-delay induced at the intersection for both automobile users and transit riders. The results suggest, therefore, that at-grade LRT solutions that employ priority measures may be warranted for a wider range of situations than previously deemed appropriate. The design situation used for illustration is the insertion of LRT into an existing highway median. However, the methodology used to evaluate overall intersection performance, both with and without priority treatment for LRT, is applicable to other design situations as well. It is recommended that additional research be conducted by applying the person-delay criterion to other design situations. It is hoped that ultimately a set of warrants will be adopted for LRT priority treatments that are based on the person-delay criterion.

This paper initially addresses current LRT planning and design practice for determining the feasibility of inserting LRT into existing street medians. The criterion used is the traditional traffic engineering practice of estimating intersection level of service with and without LRT, and with and without priority treatment. This design illustration is taken from the initial draft of a report prepared for UMTA.[1] In this paper, the level of service evaluation criterion used in the UMTA research is compared to the total person-delay evaluation criteria. The results of the Light Rail Surface Operations Report are first summarized. The particular design situation examined is the placement of a 2-track light rail line into an existing median located in the center of a heavily traveled arterial. Several design variations are discussed to illustrate possible geometric changes required in the location of motor vehicle traffic lanes due to the additional right-of-way needed for station platforms. A range of cross-traffic volumes is considered. The impacts in terms of traffic congestion due to traffic signal preemption in favor of the light rail vehicle are examined parametrically, not only for cross-street vehicular volumes but also for various LRV headways and different station platform locations. The analysis performed for UMTA suggests that surface operation of LRT should be accommodated only when excessive impacts (where "excessive" is defined by the intersection utilization reaching a certain level) on the movement of motor vehicles and pedestrians can be avoided.

THE ILLUSTRATIVE EXAMPLE

The specific design situation evaluated herein from the Light Rail Surface Operations Report is the case where the light rail line is assumed to be accommodated in an existing 50-ft-wide median of a 130-ft-wide arterial. Because of the street's width, no substantial changes to the roadway were contemplated for the arterial's two 40-ft-wide one-way roadways. Two traffic lanes and one parking lane were assumed to exist. The prototypical arterial section is shown in Figure 1. Two different types of intersections were investigated: major 4-lane cross streets with turning lanes, and 2-lane minor cross streets with no turning lanes. Traffic signals were assumed for each intersection type. Left-turn bays were assumed to exist at the major street crossing.

Geometric Design

Several different geometric design treatments for light rail were investigated, including closure of minor street crossings, both near- and far-side LRT station locations, alternative traffic signalization schemes, and the differing effects of alternative platform locations on on-street parking. Figure 2 shows a configuration with station platforms located on the far side of the crossing, opposite left-turn lanes. This arrangement permits optimum use of the available street space, because special left-turn traffic signal phases would be provided at station locations. At other similar intersections, left turns could proceed without a protected signal phase. Left turns would be prohibited at minor intersections.

Figure 3 shows one of the alternative geometric designs that was investigated; this design places the station platforms on the near side of the intersection next to left-turn lanes. This requires parking to be removed and the approach lanes to be shifted toward the curbs to provide space for the left-turn lane. This would result in the loss of about 30 percent of the parking supply on one block for both station platforms. Figure 4 shows another alternative, which shifted the alignment of the LRT track to provide space for a left-turn lane. This design would allow complete retention of the existing curb parking supply but necessitates reverse curves on the LRT tracks. With the geometry shown, the curves could have radii of about 1500 ft with no spirals. This would permit a maximum LRT operating speed of about 30 mph through the curves.

Preferential Control of LRT Movements

Intersection traffic control in these examples would be provided by standard traffic signal indications, and LRV movements would be accommodated by any of several preferential control strategies. The draft Surface Operations Report[1] suggests that selection of the appropriate strategy is a function of the degree of transit priority deemed appropriate for light rail, the traffic volume and capacity of the intersection, the type of traffic signal system, and the intensity of LRV movements.

It is further suggested in the Surface Operations Report that conflicts with pedestrians could be controlled by the existing pedestrian signals and/or could be supplemented by pedestrian signals mounted on the median on either side of the tracks. In addition, warning signs and/or audio signals could be placed on either side of the tracks to warn of approaching LRVs.

EVALUATION METHODOLOGY

To illustrate the effect of at-grade light rail operation on

Figure 1. Typical cross section for median light rail treatment.

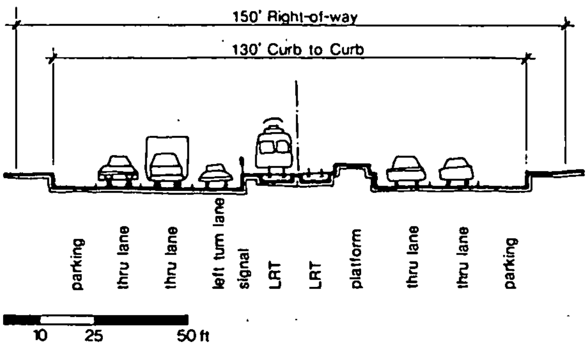


Figure 2. Major crossing with far-side platforms.

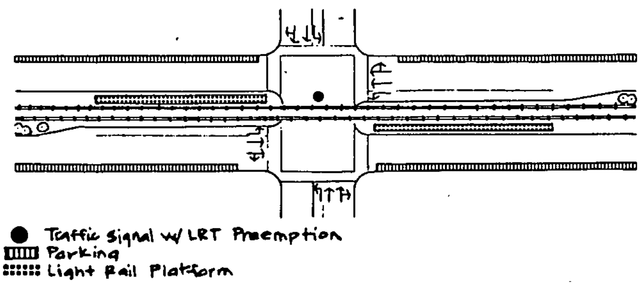


Table 1. Interpretation of levels of service for city streets.

Operation	Factor[a]	Utilization Interpretation[b] (During Peak Periods)
Excellent	to 50	Relatively free flow, average speeds 30 mph (constrained only by roadway alignment and/or speed limits)
Very good	50-75	Stable flow, slight delay at key intersections, average travel speed 25+ mph
Good	75-85	Stable flow, occasional delay and intervehicular conflicts at many intersections, average speed reduced to 20+ mph
Fair	85-95	Approaching unstable flow, delays at critical intersections as long as 2 or more signal cycles, average speed as low as 15 mph
Poor	95-100	Unstable flow, continuous backups on approaches to critical intersections, traffic from minor cross streets has difficulty entering or crossing main traffic stream, average speed likely to be at or below 15 mph
Forced flow	100 or greater	Vehicles back up from critical downstream signals through upstream signalized intersections, stop-and-go conditions, average speed less than 15 mph

[a]Percent of theoretical capacity.

[b]As defined in the Highway Capacity Manual, 1965.

these different intersection configurations and traffic characteristics, the Surface Operations Report authors prepared detailed intersection capacity calculations using techniques outlined in the Highway Capacity Manual, 1965. The concept of "level of service" was used, correlating traffic volumes and intersection capacity data with projected average travel speeds and subjective descriptions of travel performance, as shown in Table 1. The intersection utilization factors used in the analysis indicate the percentage of theoretical capacity of the intersection that is being used. The report suggests that typical urban traffic design practice adopts the "good operation" category as the design standard, with a utilization factor of 85 percent of capacity often considered the dividing line between good and poor traffic conditions. The authors further indicate that local policies may alter this standard, because what is acceptable at one intersection may not be so at another, and an acceptable standard in one community may not be another's. For the purpose of illustration, the 85 percent point was adopted as an indicator of changes in vehicular operating conditions from "good" to "poor" due to the incorporation of LRT. The report's authors suggest that combinations of LRT operating frequencies and traffic volumes that cause the utilization factor at an intersection to exceed 85 percent are taken to indicate circumstances that may call for grade separation, alternate LRT routing, increased LRV headways, or provision of alternative routings for motor vehicles.

Figure 3. Major crossing with near-side platforms: parking removed.

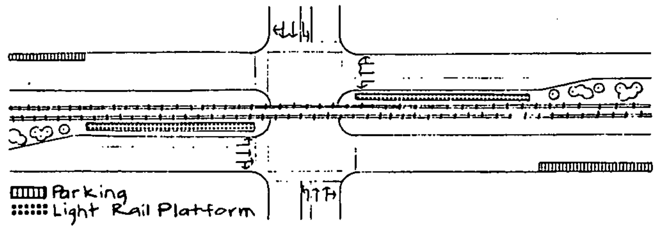
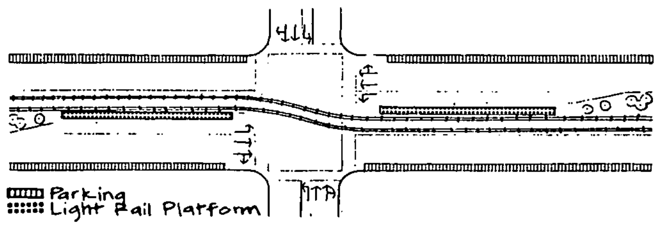


Figure 4. Major crossing with near-side platforms: no parking removed.



Intersection utilization factors (or volume/capacity ratios) using a range of traffic parameters were calculated for the various designs. Calculations were made for the unconditional traffic signal preemption control strategy in order to demonstrate the theoretical "worst case" impacts on auto traffic. Preemption intervals of up to 20 seconds were used, including time for driver reaction and clearing the intersection of vehicles blocking the track. The signal cycle was assumed to be 60 seconds. Utilization factors were calculated for three alternative operational strategies:

- Left turns from the arterial onto the cross street (across the LRT tracks) controlled with a special signal phase;
- Left turns prohibited from the arterial onto the cross street; and
- All traffic stopped during LRV passage.

The utilization factors without LRV preemption were also included for comparison. In this case, the LRV would be subject to the same signal phasing as motor vehicle traffic on the arterial. It was assumed that when left turns across the track are permitted, the LRV would be given a red signal to clear the intersection for the motor vehicle left-turn phase.

The LRV approach speed was assumed to be 40 mph, the LRV trains were assumed to be 200 ft long, and the intersection crossings were assumed to be 1, 3, 5, and 10 minutes, i.e., 2-, 6-, 10-, and 20-minute light rail headways.

Utilization factors were not calculated for LRT operation with unconditional signal preemption and near-side platforms, because with near-side platforms the time required to stop and serve passengers prior to crossing the preempted intersection is variable. With preemption it is necessary to compensate for this uncertainty by placing a light rail vehicle detector at the LRV stop line to detect when the vehicle begins to proceed. The variation in dwell time means that this detection, and hence the initiation of the signal preemption sequence, could occur at any time within the signal cycle with near-side platforms. Consequently, the impact of preemption on intersection level of service was felt to be too difficult to quantify.

Analysis of the Results

Table 2 shows the results of the analysis of the major cross street for two alternative treatments of left turns, for the LRT design alternatives shown in Figures 3 and 4, with unconditional preemption granted to the light rail vehicles. In Figure 5 the utilization factor is plotted against the cross-street volume for a range of LRT headways for the controlled left turns alternative. The results show that many of the potential situations fall in the so-called unacceptable range, thereby implying that LRT may not be acceptable in an at-grade configuration in many situations. It should be noted that these results were obtained for the design situation where all left turns are assumed to be signal-controlled. As shown in Table 2, prohibition of left turns reduces the utilization factors by 4 or 5 percentage points across the range of cross-street volumes.

Analysis of these results points out a key conceptual difficulty with the use of the traditional level-of-service approach. The results imply that, as the frequency of the LRT operation increases, the feasibility of preemption decreases because it causes an "unacceptable" impact on cross traffic. However, higher frequency LRT operation actually may mean that a far greater number of people are traversing the intersection with light rail than without it, thereby greatly increasing the overall person-carrying capacity of the intersection. Thus, the true situation may be just the opposite from that implied by the results: Traffic signal preemption may be easier to justify for high-frequency LRT lines than for lower ridership, low-frequency lines.

TOTAL PERSON-DELAY AS AN EVALUATION CRITERION

The use of intersection level of service, or of the inter-

Figure 5. Utilization factor versus cross-street volume for a range of LRT headways (with preemption).

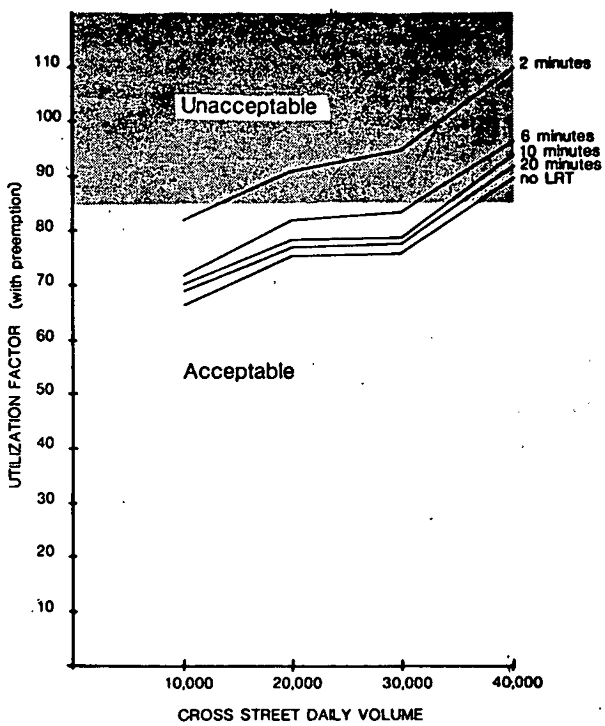


Table 2. Effect of preemption for light rail on peak-hour utilization rates at an intersection with a major cross street.

			LRT Headway (minutes)				
			2	6	10	20	-
			Intersection Crossing Interval (minutes)[a]				
Preempt Strategy	Platform Location	Cross-Street Volume	1	3	5	10	No LRT
A. Parallel traffic moves with LRT, left turns controlled	Far side or none	10K[b]	82 (76)	72(66)	70(64)	69(63)	67(62)
		20K[b]	92	81	78	77	76
		30K[c]	95	83	80	80	78
		40K[c]	110	97	93	92	91
B. Parallel traffic moves with LRT, no left turns	Far side or none	10K[b]	77 (82)	67(72)	65(70)	65(69)	63(67)
		20K[b]	87	76	74	73	72
		30K[c]	90	79	76	75	74
		40K[c]	106	93	90	89	87

Note: Figures in parentheses assume pedestrian actuation every other cross-street phase.

[a]Intersection crossing interval equals one-half the headway operated in each direction.

[b]Two lanes plus parking.

[c]Three lanes, no parking.

section utilization factor, as the sole evaluation criterion considers only automobile passengers and drivers. If, however, a criterion can be developed that considers the impact of alternative design treatments on both auto and transit users, then a more comprehensive evaluation will result. The criterion of total person-delay would measure the overall impact on the movement of people, rather than simply on the movement of autos. To use this criterion it is necessary to estimate the total person-delay resulting from the incorporation of light rail into the median of our hypothetical street.

Delay to Auto Drivers and Passengers

May and Pratt estimated the average delay to individual autos as a function of load factor defined as in the Highway Capacity Manual, or the proportion of green signal intervals that are fully utilized in the peak hour.[2] In addition, Crommelin related the load factor to the intersection utilization factor.[3] By combining these results, it is possible to estimate the average individual vehicle delay as a function of the intersection utilization factor. Table 3 shows the actual combined results from May and Crommelin.

Figure 6 shows the relationship graphically. Regression analysis performed on the data suggests that a power curve provides the best fit (with $r^2 = 0.97$):

$$\text{Delay} = 0.22\ e^{5.77\ (\text{IUF})}$$

where e = base of Napierian logarithms and IUF = intersection utilization factor. By apply this formulation to the results of the Surface Operations Report, it is possible to estimate the total delay to automobile users resulting from implementing light rail into our hypothetical arterial. Table 4 shows the delay to auto users resulting from unconditional preemption for light rail for the same hypothetical major intersection. The figures represent the induced delay in person-hours for a single peak hour.

Delay to Light Rail Passengers

It is possible to estimate the total delay to light rail passengers that would result if light rail were not to be granted preemption. This analysis can be made parametrically, but for the purposes of this paper, to make this estimate the following was assumed:

- Time lost in deceleration and acceleration is neglected;
- Cycle length is 60 seconds with 50/50 split;
- The 3-car LRV train is approximately 240 ft long;
- The LRVs are fully loaded (160 passengers) in the peak direction;
- The LRVs are half full in the off-peak direction; and
- There is no signal progression (random arrival at any point in the signal cycle).

For these simplifying assumptions, the total peak-hour delay to transit passengers is shown in Table 5. This represents the expected delay in person-hours over the entire peak hour, assuming vehicles are equally likely to arrive at the signal at any point in the signal cycle.

By subtracting estimated auto user delay (from Table 4) from these figures, it is possible to determine the net overall person-delay avoided by preemption. Table 6 shows these results, which are also expressed in person-hours for a single peak hour.

Analysis of the Results

Figure 7 plots the net savings in delay due to preemption against the cross-street volume. The results here can be compared against those shown in Figure 5 for the more conventional effectiveness measure, the utilization factor. Some striking differences are evident. First, the delay criterion gives results that are more consistent with the objective of maximizing the overall person-carrying capacity of the intersection—namely, as the frequency of LRT service increases, the savings in overall person-delay also

Table 3. Relationship between load factor, intersection utilization factor, and average vehicle delay.

Level of Service	Load Factor	Intersection Utilization Factor	Average Vehicle Delay (seconds)
A	0.0	0.68	10.0
B	0.1	0.71	15.0
C	0.3	0.77	18.5
D	0.7	0.90	39.0
E	1.0	1.00	--

Figure 6. Average individual vehicle delay versus intersection utilization factor.

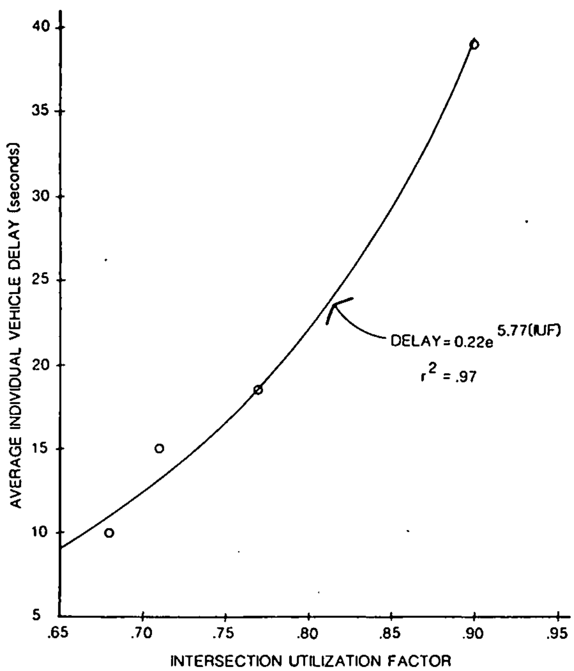


Table 4. Auto user delay.

Preempt Strategy	Cross-Street Volume	Auto Person-Hours of Preempt-Caused Delay: LRT Headway (minutes) 2	6	10	20	No LRT
A. Left turns controlled	10K	5.2 (3.5)	1.3 (0.7)	0.7 (0.3)	0.5 (0.1)	0
	20K	19.4	4.3	1.6	0.8	0
	30K	35.8	7.1	2.6	2.6	0
	40K	∞	25.0	7.4	3.6	0
B. No left turns	10K	3.8 (5.2)	0.8 (1.3)	0.4 (0.7)	0.4 (0.5)	0
	20K	13.9	2.6	1.2	0.6	0
	30K	25.8	5.7	2.1	1.0	0
	40K	∞	19.8	9.0	5.8	0

Note: Assumptions are the same as for Table 2, plus a 10 percent peak-hour factor and an average auto occupancy of 1.3.

increase. It must be pointed out, however, that in the illustrative example, as cross-street volumes approach 40 000 and headways reach about 6 minutes, the delay to autos becomes quite significant. Thus, the justification for priority treatment for LRT generally increases as the line volume increases, until the headways are so short and cross-street volumes are so high as to begin to greatly increase auto delay. Second, it is found that preemption can be justified for all but two of the combinations of LRT headways and cross-street volumes, whereas the utilization factor criterion resulted in many more design situations falling into the so-called unacceptable category.

CONCLUSIONS AND RECOMMENDATIONS

Much additional research is needed before warrants for signal preemption can be adopted based on the total person-delay criterion. However, the results obtained in this analysis certainly suggest that the technique would yield design decisions that are more consistent with maximizing the person-carrying capacity of the street space of cities. It is recommended that additional research be conducted, with emphasis given to addressing the following issues:

- Consider the effects on other adjacent intersections, rather than just on an isolated intersection.
- Consider the additional delay due to motorists seeking alternative routes.
- Include the additional delay to light rail passengers due to deceleration and acceleration for stops that otherwise would not need to be made.
- Consider the effect of providing signal progression for light rail along the length of the line.
- Consider the effect of conditional preemption, such as granting early or extended green for light rail.
- Extend the analysis to a wider range of generic geometric design situations.
- Compute net annual savings in delay and convert to dollars using an appropriate value of time. Compare the value of time savings (or time lost) to the cost of a grade separation to determine if a separation is justified.

Such research would be aimed at adopting a set of warrants for priority treatment for light rail. Decisions regarding grade separations then, it is hoped, would begin to be made on a sound technical basis. Unfortunately, design decisions are often made to grade-separate new light rail lines on grounds other than maximum use of the right-of-way to carry people in the most cost-effective manner. In the present era of limited capital funding for

Figure 7. Person-hours of delay saved by preemption versus cross-street volume (for the controlled left-turn case).

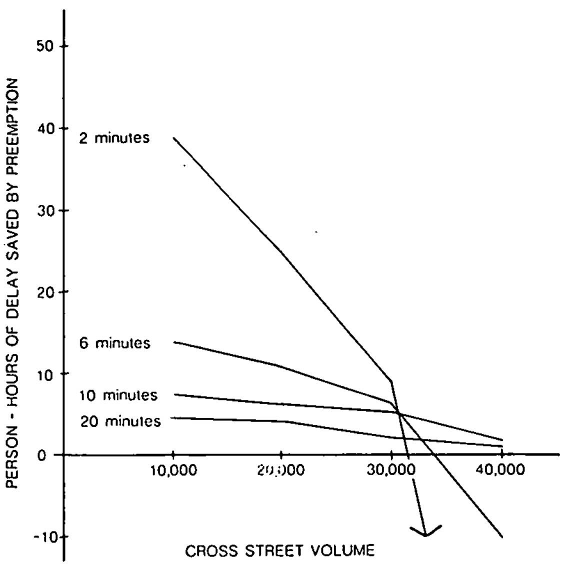


Table 5. Transit person-hours of delay in peak hour without preemption.

Headway (minutes)	Person-Hours of Delay
2	45
6	15
10	9
20	4.5
No LRT	—

Table 6. Net person-hours of delay avoided by preemption during peak hour.

Preempt Strategy	Cross-Street Volume	LRT Headway (minutes) 2	6	10	20	No LRT
A. Left turns controlled	10K	39.8	13.7	8.3	4.0	-
		(41.5)	(11.5)	(8.7)	(4.4)	
	20K	25.6	10.7	7.4	3.7	-
	30K	9.2	7.9	6.4	1.9	-
	40K		-10.0	1.6	0.9	-
B. No left turns	10K	41.2	14.2	8.6	4.1	-
		(39.8)	(13.7)	(8.3)	(4.0)	
	20K	31.1	12.2	7.8	3.9	-
	30K	19.2	9.3	6.9	3.5	-
	40K		4.8	0	-1.3	-

Note: Figures in parentheses assume pedestrian actuation every other cross-street phase.

transit, the importance of this issue cannot be overstated, because at-grade solutions may be the only affordable high-capacity transit option for many cities dependent on local funding capability.

REFERENCES

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2. Adolf May, Jr., and David Pratt. "A Simulation Study of Load Factor at Signalized Intersections." Traffic Engineering, February 1968.

3. Robert W. Crommelin. "Employing Intersection Capacity Utilization Values to Estimate Overall Level of Service." Traffic Engineering, July 1974.