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Evaluating Capacities of One-Lane Roads with Turnouts

FONG-LIEH OU

ABSTRACT

Speed-flow relationship models for one-lane roads with two-way traffic are developed. Each model considers a composite variable of speed divided by the traffic distribution ratio as a dependent variable and both traffic distribution ratio and volume as independent variables. The traffic distribution ratio represents the degree of traffic conflict and is measured as the percentage of one-way traffic on the heavy-traffic direction to total traffic. A 1982 traffic survey of four study sites in the Mount St. Helens Monument region forms the data base. The following are specific findings of the study: (a) Model specification and coefficients, including elasticities, are stable. (b) The capacity of a single-lane road with turnouts may exceed 400 vehicles per day without reaching the congested-flowing situation when the majority of traffic is controlled by citizen band radios. (c) Speed is more sensitive to traffic distribution than to volume. (d) The predictive ability of the developed models has been validated at nine study sites with satisfactory results. The results of this study provide road engineers and managers some guidelines for selecting the most cost-effective design standard and management strategy for one-lane roads with turnouts.

The Highway Capacity Manual (1,p.5) defines capacity as "the maximum number of vehicles which has a reasonable expectation of passing over a given section of a lane or a road in one direction (or in both directions for a two-lane or a three-lane highway) during a given time period under prevailing roadway and traffic conditions." This definition is not applicable to a one-lane road with turnouts that is managed for two-way traffic. The reason for building one-lane roads with two-way operation is that low traffic demand cannot economically justify building multilane roads. Multilane roads provide a high level of service, but they require a great amount of traffic demand to offset high construction and maintenance costs. The configuration of a typical one-lane road with turnouts is shown in Figure 1. The width of one lane ranges from 12 to 14 ft.

The U.S. Department of Agriculture Forest Service is probably the largest organization in the world to promote and manage two-direction traffic on one-lane roads with turnouts. Over the years, the Forest Service has built a 270,000-mile forest road system. More than 72 percent of the system consists of one-lane roads. The design standards of one-lane roads were determined by either speed or travel-time delay based on the 1960 Logging Road Handbook: The Effect of Road Design on Hauling (2). It was not until 1981 that volume was considered one of the criteria for evaluating traffic service (3). However, because the mathematical relationship between volume and traffic performance has not been defined, there is difficulty implementing this new concept. Volume is used primarily for determining long-term traffic demand (such as daily, seasonal, and annual traffic) rather than short-term system supply (such as hourly volume) in terms of capacity.

Defining capacity of forest roads is difficult because the traffic on them rarely reaches capacity. In 1982 it was expected that certain road segments in the Mount St. Helens Monument region might exceed their design capacity because, as a result of the May 18, 1980, volcanic eruption, approximately 900 million board feet of salvage timber were scheduled to be hauled to market in two seasons. The Forest Service took this opportunity to select 22 sites for a traffic study. Although the preliminary results concerning speed related to design standards have been reported elsewhere (4), the data collected in this study also permit an analysis of the relationship between volume and traffic performance to assess the capacity of low-volume roads.

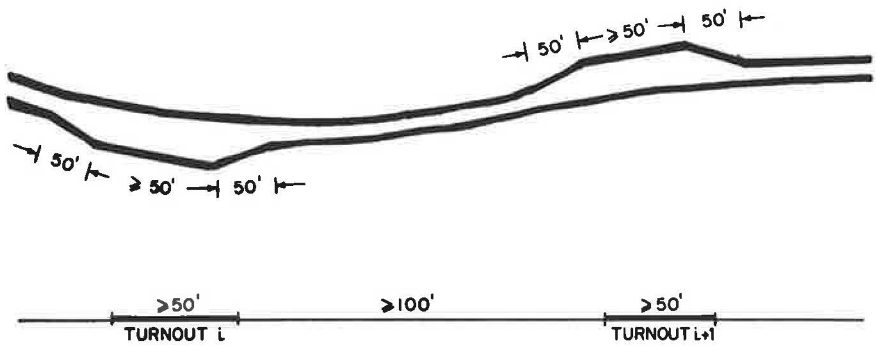

FIGURE 1 Configuration of one-lane roads with turnouts.

The purpose of this study was to compare lane capacity of single-lane roads with various design standards. The results of this study should not be used to determine the flow, average speed, or density at capacity for low-volume roads unless the traffic is controlled by citizen band (CB) radios.

BASIC CONCEPTS

The principal characteristics of traffic are flow, speed, and density. The fundamental characteristics are dependent on the geometric design of the roadway, the composition of the traffic stream, the consistency of road maintenance, and combinations of the three. The importance of these characteristics is manifested by the need for specific indications of impending traffic congestion, which can be used either in control processes intended to maintain optimum efficiency of an existing road system or in designing processes intended to obtain optimum cost-effectiveness of a new road system.

The relationship between flow (q), average speed (u), and density (k) can be shown by

$$q = k \times u \quad (1)$$

The functional relationships between any pair of variables are shown in Figure 2 and may be mathematically expressed by

$$u = u(q) \quad (2)$$

$$u = u(k) \quad (3)$$

$$q = q(k) \quad (4)$$

Of these functional relationships, the speed-flow relationship shown in Figure 2(a) is usually the basis for highway capacity analysis. The portion of the curve with the solid line denotes free-flowing conditions, and the portion of the curve with the dotted line represents congested-flowing conditions. During free-flowing conditions, speed decreases corresponding to the increase of flow. On the other hand, in congested-flowing conditions, flow decreases from capacity flow corresponding to the decrease of speed.

A number of studies have been devoted to evaluating the capacity of multilane high-volume roads (1,5). Capacity in terms of the speed-flow relationship plays an important role (along with other parameters such as speed, travel time, and freedom to maneuver) in defining the level of service of multilane high-volume roads. Level of service represents the quality of service being provided to the drivers who use the facility. The capacity of one-lane urban highways has been investigated in construction and reconstruction work zones (6,7). The results of these studies indicated that the lane capacity of one-lane roads differs significantly from that of multilane roads. The studies also found that on a two-lane highway, one-way and two-way traffic would result in different degrees of freedom to maneuver and thus affect lane capacity (7).

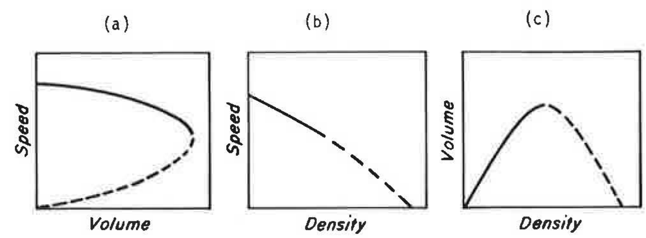

FIGURE 2 General relationships between traffic volume, speed, and density.

DATA SOURCE

The procedure of data collection and the road characteristics of study sites have been reported elsewhere (4). All road segments were used for speed-volume analysis, but only four of them were selected for capacity evaluation. Road characteristics of these four selected sites are given in Table 1. Except for grade, the design standards of these road segments are different. Sites 17 and 20 are paved, and sites 26 and 33 are gravel. Both sites 17 and 26 have good alignment and sight distance. Site 33 has good alignment and fair sight distance, and both design criteria for site 20 are fair.

The data are characterized by traffic volume, traffic composition, and weather condition (Table 2). The average volume ranges from 13 vehicles per hour (vph) at site 26 to 30 vph at site 33. This figure is relatively low compared with that of an urban highway system. The single-lane capacity of an urban highway (maximum 5-min flow) could be as high as 1,600 vph (7). The majority of the traffic was

TABLE 1 Road Characteristics of Study Sites

	Site			
Characteristics	17	20	26	33
Type of road	Single lane	Single lane	Single lane	Single lane
Type of surface	Paved	Paved	Gravel	Gravel
Alignment	Good	Fair	Good	Good
Grade (percent)	4.1	5.9	3.9	5.8
Sight distance	Good	Fair	Good	Fair
Template for passing	Yes	Yes	Yes	Yes
Length of road segment (miles)	0.93	1.20	0.58	2.10

TABLE 2 Data Characteristics

Site	Date of Observation	Duration of Traffic Count	Average Hourly Volume	Traffic Composition (%) Light Vehicles	Forest Service Light Vehicles	Recreational Vehicle with Trailer	Empty Log Truck	Loaded Log Truck	Other Truck	Weather Condition
17	June 17, 1982	10:57 a.m.-2:00 p.m.	31	17	2	0	28	20	33	Clear, warm
	Aug. 25, 1982	10:15 a.m.-2:10 p.m.	34	29	4	0	18	49	0	Clear, warm
	Average		32	22	3	0	24	32	19	
20	June 29, 1982	12:44 p.m.-3:20 p.m.	30	36	8	0	12	32	12	Cloudy, cool
	July 28, 1982	6:20 a.m.-10:20 a.m.	16	37	16	0	13	30	4	Patchy
	Aug. 25, 1982	5:50 a.m.-8:20 a.m.	17	24	8	0	23	40	5	Clear, warm
	Average		20	32	11	0	17	34	6	
26	June 30, 1982	7:53 a.m.-10:53 a.m.	10	23	10	0	30	30	7	Cloudy, rain
	July 28, 1982	12:01 p.m.-2:10 p.m.	13	41	31	0	7	21	0	Clear
	Aug. 26, 1982	5:20 a.m.-8:50 a.m.	17	44	1	0	29	21	5	Clear, warm
	Average		13	38	11	0	24	23	4	
33	July 1, 1982	8:00 a.m.-11:20 a.m.	37	17	7	0	45	28	3	Cloudy
	July 26, 1982	2:00 p.m.-3:10 p.m.	37	40	3	0	7	16	0	Partly cloudy
	July 28, 1982	11:00 a.m.-1:35 p.m.	43	18	6	0	31	41	4	Overcast with fog
	Aug. 26, 1982	5:50 a.m.-8:40 a.m.	38	19	1	0	27	47	6	Clear
	Average		39	21	0	0	32	39	3	

empty log trucks and loaded log trucks, which accounted for from nearly 50 to more than 70 percent of the total traffic. The portion of other trucks differs greatly, ranging from 3 percent at site 33 to 19 percent at site 17. This discrepancy was caused by the reconstruction of a road segment near site 17 on June 17, when the traffic count took place. The portion of Forest Service light vehicles varied from 3 percent at site 17 to 11 percent at sites 20 and 26. No recreational vehicles were observed because the road segments in the study area were not open to the public during the study period.

Using the data collected from each site, the duration of the traffic count was broken down into several intervals, with each interval containing an independent, continuous flow. The gaps between intervals are longer than 4 min, and the intervals range from 5 to 35 min. The average hourly volume was expanded from the traffic of each interval.

Three variables for the analysis are speed, volume, and the degree of traffic conflict. The degree of traffic conflict is represented by the percentage of traffic in the heavy-traffic direction relative to total traffic. The ratio is 50 percent when the traffic in two directions is equal. On the other hand, the ratio is 100 percent if the flow becomes one-way traffic. Most vehicles were equipped with CB radios. When a traffic conflict occurred, the loaded log truck had the right-of-way. Other vehicles were required to yield the way to loaded log trucks by using turnouts as safe bay areas.

Design standards such as alignment and site distances were not selected for defining the speed-flow relationship for two reasons. First, the sample of study sites is too small. Second, the design standards for this study were not quantitatively defined. Using qualitative variables for modeling would require a sizable sample to produce meaningful results.

MODEL CALIBRATION

The first step in defining the capacity of a road is to examine the relationship between speed and volume. The speed-volume relationship for 13 study sites is shown in Figure 3. Each dot represents the result of a traffic count during a period ranging from 2 to 3 hours. Dots that apply to the same site are connected by solid lines. The ultimate practical capacity is expressed by the dashed line. Note that the ultimate practical capacity is defined as the maximum practical speed corresponding to a particular volume.

The figure reveals several remarkable features of speed-volume relationships. First, speed-volume relationships vary among study sites. This variation is affected by design standards and traffic characteristics as reported elsewhere (4). Next, the speed-volume relationships observed at a given site are inconsistent. Traffic performance at most sites follows the rule of thumb that an increase in volume tends to decrease speed. However, at some sites speed was not sensitive to volume, whereas at others speed increased as a result of high volume. This inconsistency indicates that capacity cannot be defined without consideration of other traffic characteristics such as traffic conflict. The third feature shown in Figure 3 is that the operation of two-way traffic on one-lane roads with turnouts is governed by the ultimate practical speed-volume curve shown by the dashed line. This indicates that one cannot expect a log truck to travel on one-lane roads at 30 mph when the volume reaches 40 vph. Finally, the figure shows that the majority of traffic can operate at a speed ranging from 20 to 30 mph with the volume between 15 and 40 vph, or 150 and 400 vehicles per day (vpd). This finding is vitally important because the Forest Service Transportation Engineering Handbook requires the construction of double-lane roads to meet the demand when traffic

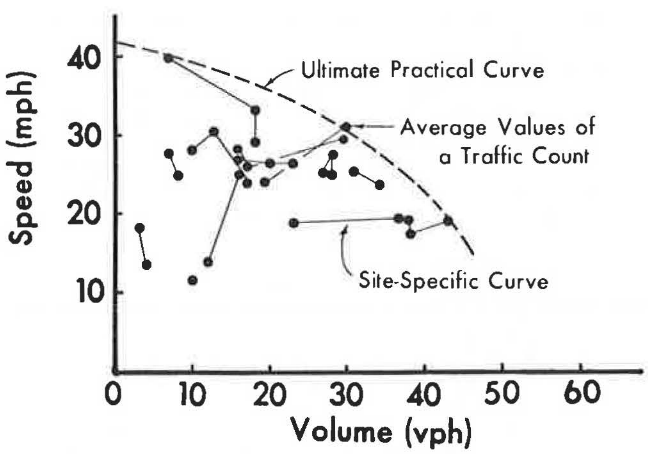

FIGURE 3 Speed-volume relationship of one-lane roads with turnouts.

volumes are greater than 250 vpd (3). Use of 400 vpd as a benchmark for determining the need for double-lane roads could save a considerable amount of transportation cost annually.

The foregoing discussion indicates that defining capacities of single-lane roads is difficult but manageable. Using the data derived from each of four selected sites for capacity analysis may exclude the impact of design standards on speed and, hence, reduce the difficulty to a minimum. Graphic analysis of these derived data revealed that speed-flow relationships between one-way and two-way traffic flows are significantly different. As expected, the traffic distribution between the two ways of travel plays an important role in affecting traffic performance. The greater the existing traffic conflict, the lower the speed. Although the impact of traffic conflicts on speed was reduced to a minimum because most vehicles were equipped with CB radios, psychologically drivers did not treat two-way traffic as one-way traffic (6). Thus the degree of freedom to maneuver for two-way traffic is lower than that for one-way traffic. For example, two-way traffic requires twice the sight distance acceptable for one-way traffic.

Because the speed-flow relationship is nonlinear, several nonlinear curves (e.g., product, logistic, exponential, logarithmic, and mix-logarithmic forms) have been used to simulate the relationship of speed with traffic volume and distribution ratio. By trial and error, a mix-logarithmic model has been found to fit most of the data well:

$$Z = a_o - a_1C' - a_2V \quad (5)$$

where

- Z = a composite variable equal to U/C,
- U = average speed (mph),
- C = traffic distribution ratio (percent of one-way traffic on heavy-traffic direction to total traffic that ranges from 13 to 33 vph),
- C' = logarithmic value of C,
- V = volume (vph), and
- a = constant to be estimated.

Four models based on Equation 5 have been developed. The composite variable of speed to traffic distribution is highly related to both explanatory variables, with the coefficient of determinant, R^2, ranging from 0.7073 to 0.8527 (see Table 3). However, it should be noted that such a relationship is valid only within the range of base conditions from which models were developed. Such a relationship is subject to further investigation to see whether it holds when the base conditions of a new environment are out of this range.

STABILITY ANALYSIS

A comparison of the variable coefficients of four models (Table 3) shows that the speed-flow relationship is stable. When the composite variable of speed divided by traffic distribution ratio is considered as the dependent variable, the constants of these models range from 1.41573 for site 33 to 1.79683 for site 26. The coefficients of traffic distribution ratio range from 0.2637 for site 33 to 0.3197 for site 20, and the coefficients of volume fall in the range of 0.000282 for site 33 to 0.000371 for site 26. The differences are small compared with those of the design standards and traffic characteristics of the study sites.

Model stability can be further examined by traffic characteristics elasticity expressed as the change in the quantity of traffic performance by drivers in response to a 1 percent change in traffic characteristics. When the elasticity is 1.0, it is called unit elasticity. The elasticity is unelastic if it is less than 1.0 and is elastic if it is greater than 1.0. Two types of elasticities can be derived from Equation 1: volume elasticity

$$\eta_U = a_2VC/U \quad (6)$$

and traffic distribution elasticity

$$\eta_{TD} = C/U(U-a_1) \quad (7)$$

In accordance with Equations 6 and 7, elasticities for the four sites were calculated (Table 4). Table 4 reveals that all derived elasticities are inelastic (i.e., the value is less than unity). The result can be explained by using site 17 as an example. If a traffic management policy is to impose a limited control on one-way traffic to improve site 17 road system efficiency, reducing the traffic distribution ratio (percent of one-way traffic with heavy traffic to the total traffic) 1 percent will result in a 0.1228 percent speed increase. On the other hand, if the policy is to reduce volume, a 1 percent decrease in traffic volume will increase speed by 0.0665 percent. Elasticity can be a useful tool for decision makers who compare costs and benefits to determine a traffic management strategy.

TABLE 3 Speed-Flow Models and Base Conditions

		Base Conditions								
		Speed (mph)			Hourly Volume (vph)			Traffic Distribution (% of one-way to total)		
Site	Speed-Flow Models	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
17	$U = (1.53354 - 0.27094C' - 0.000354V)C$ $R^2 = 0.8527$; $F = 92.64$ D.F. = 32; D.W. = 2.4410	26.2	31.5	18.8	59	200	5	83.4	100	50
20	$U = (1.79683 - 0.31966C' - 0.000292V)C$ $R^2 = 0.7115$; $F = 51.79$ D.F. = 42; D.W. = 1.5517	29.8	44.2	20.9	80	250	3	80.4	100	50
26	$U = (1.72195 - 0.30365C' - 0.0003713V)C$ $R^2 = 0.7073$; $F = 41.08$ D.F. = 34; D.W. = 1.7391	29.6	37.3	22.1	55	160	6	79.1	100	50
33	$U = (1.41573 - 0.26369C' - 0.000282V)C$ $R^2 = 0.8296$; $F = 114.42$ D.F. = 47; D.W. = 1.2695	19.3	25.5	12.2	71	260	15	79.2	100	50

Note: U = average speed (mph), C = percentage of one-way traffic on the heavy-traffic direction to total traffic (range from 50 to 100), C' = logarithmic value of C, and V = average hourly volume (vph).

TABLE 4 Traffic Characteristics Elasticities

	Elasticity	
Site	Flow	Traffic Distribution
17	-0.0665	0.1228
20	-0.0764	0.0915
26	-0.0520	0.0927
33	-0.1031	0.2156

Examination of Table 4 indicates that the derived elasticities are stable. Both elasticities for sites 17, 20, and 26 are identical. The flow elasticities range from -0.0520 for site 26 to -0.0764 for site 20, and the traffic distribution elasticities are within the range of 0.0915 to 0.1228. The elasticities for site 33 are higher than those for the other sites. They are -0.1031 and 0.2156 for flow and traffic distribution elasticities, respectively. This differentiation indicates that the traffic management policy can be a more effective option when applied to site 33 than when applied to other study sites. Comparison of elasticities for both traffic characteristics indicates that the effect of traffic distribution on speed is more sensitive than is that of volume. Traffic distribution elasticity is approximately twice volume elasticity.

MODEL VALIDATION

To validate the developed models, nine sites from the study area were selected for application. These sites are given in Table 5. As indicated in the table, the first four sites are the study sites where the models were developed. These four sites were selected to check whether the speed-flow models developed from a site can be used to predict the average speed of that site. The data in the table indicate that at sites 17, 20, 26, and 33 the discrepancies between the observed speeds and the speeds estimated by their own models are less than 1 percent. The result indicates that a model developed from a particular site is capable of predicting speed at that site. Note that the data used for model development were derived from two to four traffic counts, whereas the data for validation are based on one traffic count.

The next concern of model validation is to examine the spatial transferability of the developed models. The data given in Table 5 reveal that the result of applying a model developed from one site to other sites is mixed. The models developed from sites 17, 20, and 26 can predict the speed at most sites with less than 15 percent error. However, the difference between the observed speed and the speed estimated by these three models can be as great as 60 percent. On the other hand, the site 33 model underestimated the speed at all sites except site 34. The error in estimation could amount to 40 percent.

The result of transferability analysis indicates that there is no warrant for applying a model developed from one site to predict speed at another site. This result was expected because the design standard of one-lane roads varies from one road segment to another and the design standard has not been considered in the model development. Use of the design standard as one of the variables to develop speed-flow models is beyond the scope of this study. However, by classifying the nine study sites into three groups in accordance with the design standard it appears that sites 18 and 21 belong to the high-standard group, sites 17, 19, 20, 25, and 26 constitute the medium-standard group, and sites 33 and 34 fall into the low-standard group. High-standard roads are defined as paved roads with good alignment, good sight distance, and flat grade; low-standard roads are gravel or dirt with poor surfacing, poor alignment, and poor sight distance, as well as steep grade. Medium-standard roads are represented by paved or gravel roads with a fair rating of alignment, grade, and sight distance.

Based on this classification, the models of sites 17, 20, and 26 can predict the speed for the sites in the medium-standard group with errors of estimate ranging from 2.2 to 13.8 percent, and the site 33 model can predict the speed at site 34 with less than 10 percent error. As expected, these four models developed from medium- and low-standard site groups underestimated the speed at sites included in the high-standard group. On the other hand, the models developed from sites with medium design standards overestimated the speed of low-standard roads.

CONCLUSIONS

Although the study of capacities of single-lane roads with two-way traffic is limited, the results reported here provide convincing evidence that the capacity of low-volume roads can be defined. Specific findings of this study are the following: (a) Four speed-flow relationship models developed from four study sites have been found to be stable in terms of model structure and coefficients, including elasticities. (b) The capacity of a single-lane road with turnouts may exceed 400 vpd without reaching the congested-flowing situation when the majority of traffic is controlled by CB radios. (c) The impact

TABLE 5 Comparison of Observed and Estimated Speed for Nine Selected Sites

	Speed									Base Conditions	
		Forecast by Models									
		Site 17		Site 20		Site 26		Site 33			
Site	Observed mph	mph	Difference (%)	mph	Difference (%)	mph	Difference (%)	mph	Difference (%)	Average Hourly Volume (vph)	Traffic Distribution (% of one-way traffic to the total)
17	25.2	25.0	-0.8	24.6	-2.2	28.3	+12.2	19.8	-21.5	27	61
20	28.2	24.3	-13.8	28.1	-0.3	27.5	-2.6	19.5	-30.9	16	55
26	28.3	25.3	-10.6	29.1	+2.8	28.5	+0.7	20.0	-29.3	10	60
33	19.9	24.9	+25.1	28.9	+45.2	28.2	+41.7	19.7	-0.1	37	62
18	31.6	23.5	-25.6	27.3	-13.6	26.6	-15.8	19.0	-39.9	30	52
19	26.0	24.9	-4.2	28.8	+10.8	28.2	+8.5	19.7	-24.2	20	60
21	29.5	24.3	-17.6	28.1	-4.7	27.4	-7.1	19.5	-33.9	18	55
25	24.9	23.5	-5.6	27.2	+9.2	26.6	+6.8	19.1	-22.0	8	50
34	18.4	25.3	+37.5	29.2	+58.7	28.6	+55.4	20.1	+9.2	37	62

Note: + = overestimated, − = underestimated.

of traffic distribution between two ways on speed is twice that of volume. (d) The developed models can yield site-specific speed estimates with margins of error of less than 1 percent. (e) The model developed from one site is capable of predicting the speed at other sites with similar design standards. The results of this study provide some general guidelines for road engineers and managers to use in selecting cost-effective road design standards and developing cost-effective road management programs for one-lane roads with turnouts.

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Abridgment

Computer Simulation To Compare Freeway Improvements

ROBERT W. STOKES and JOHN M. MOUNCE

ABSTRACT

Use of a simulation program, FREQ6PE, to compare proposed improvements for the Southwest Freeway (US-59) in Houston, Texas, is described. The simulation model was calibrated using actual field data and was then used to identify the best of a number of proposed geometric improvements. The proposed improvements were evaluated by comparing key simulated measures of effectiveness for the proposed systems with comparable measures for the base (do-nothing) system. Based on the experience gained in using the program, it is concluded that the program can be an effective and economical tool for studying the dynamic response of a freeway to a variety of input specifications.

The Southwest Freeway (US-59) bisects one of the fastest growing corridors in the Houston region. Traffic demands on the freeway outside of I-610 (see Figure 1) have increased 45 percent over the past 5 years to an average daily volume of about 194,000 vehicles. Depressed levels of service often extend from 6:00 to 9:00 a.m. and from 4:00 to 7:00 p.m., with trip times frequently tripling from off-peak to peak periods (1).